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SCIENTIFIC PROGRESS AND THE EVOLUTION OF INTERNATIONAL LAW

by

CHARLES ROUSSEAU

Professor Rousseau, of the Faculty of Law at the University of Paris, is an authority on international law. His published works include Principes généraux du droit international public, *Paris, 1944,* L'indépendance de l'Etat dans l'ordre international, *Paris, 1948, and* Droit international public, *Paris, 1953.*

It is self-evident that scientific progress directly influences the regulations governing social intercourse when one considers that the application of science brings about changes in the technological framework of society, and thus leads inevitably to new forms of civilization and a rearrangement of human relationships. However, this phenomenon does not always occur with the same persistence or intensity. It is naturally more noticeable in a social environment whose structure is more highly developed, and where the connexion between the subjects of law is closer, more frequent or more continuous. In other words, municipal law is pre-eminently the sector in which the relationship between technological progress and legal regulations may be most clearly observed.

The problem inevitably changes as we turn from municipal to international law. In the latter case the social structure is still primitive, the procedure adopted for the drafting and enforcement of laws is inadequate, and legal technique is all too frequently vitiated by political prejudice or by nationalist exclusivism; all of which would hardly seem, at first glance, to facilitate the subordination of the law of nations to the demands of scientific progress. In actual fact, however, the influence of scientific discoveries on the development of international law is far from negligible; and even a cursory consideration of the problem will reveal aspects more numerous and more complex than are usually supposed to exist.[1]

These may be grouped around three basic concepts, since the normal effect of scientific discovery, at the international level, is sometimes to extend the jurisdiction of states, sometimes to influence the system by which such

1. Bibliography on this subject is comparatively scanty. The reader is referred, in particular, to E. M. Earle, *The Impact of Scientific Discovery and Technological Change on International Relations,* Proceedings of the Eighth Conference of Teachers of International Law and Related Subjects, Washington, 1946; and M. Bourquin, 'Pouvoir scientifique et droit international', *Recueil des Cours de l'Académie de Droit International,* 1947, I, p. 335-406. The latter is chiefly concerned with the problem of atomic energy.

jurisdiction is exercised, and sometimes—the aspect most commonly perceived till now—to alter the conditions in which the law of war is applied.

EXTENSION OF THE SPATIAL JURISDICTION OF STATES

Scientific progress has often led to an extension of the spatial jurisdiction of a state, though this has not always been clearly apparent.

Artificial Frontiers

The frontier between two states has sometimes been determined, not by adopting a natural or geographical line of demarcation (such as a chain of mountains, a river or a lake), but with reference to some artificial boundary based on scientific considerations.

The phenomenon made its appearance at an early stage with regard to the adoption of *astronomical boundaries,* which followed parallels of latitude or meridians of longitude. The best known applications of this method were those resulting from the verbal agreement of Le Cateau-Cambrésis (3 April 1559) with reference to the Tropic of Cancer, supplemented by the Anglo-Spanish Treaty of Madrid, 1630 (which referred to the line of the Equator); from the Versailles Treaty of 3 September 1783, which adopted the section of the 45th parallel running from the River Connecticut to the Saint-Lawrence as the frontier between the United States of America and Canada; from the Anglo-American treaty of 6 May 1846, which adopted the 49th parallel, from the Pacific to the Lake of the Woods, as the northern line of demarcation of the same two countries; and from the Anglo-Egyptian agreement of 19 January 1899, which adopted the 22nd parallel as the frontier between Egypt and the Sudan. The decisions taken by the Allies in 1945 with regard to Indo-China (divided by the 16th parallel into two separate zones, to be occupied respectively by the Chinese and the Anglo-American forces) and Korea (divided by the 38th parallel into two separate zones) were based on a similar principle.

The meridians of longitude are more seldom used, though there is one celebrated instance—that of the Treaty of Tordesillas (7 June 1494) between Spain and Portugal, fixing the line of demarcation between the future colonies of the two countries. That treaty, which was a rectification of the Bull *Inter Coetera* (Bull of Demarcation), promulgated by Pope Alexander VI on 4 May 1493, adopted as boundary a line joining the North and South Poles and passing 370 leagues to the east of the Azores.

As for the *geometrical frontier,* another type of artificial boundary-line, it consists either of a straight line connecting two given points, or of a segment of a circle (e.g. the frontier between Egypt and Libya, the southern

frontier between Syria and the Hashemite Kingdom of Jordan, the frontier between Alaska and Canada, etc.).

Artificial lines of demarcation—which are invisible frontiers—may be an advantage or a drawback, according to the attitude of the states concerned. They have fallen almost completely into disuse nowadays, especially in Europe. And this is one of the very few cases where technological progress and the development of legal regulations have been dissociated from one another, the latter having been finally guided by different considerations.

Territorial Waters

Scientific progress has had a particularly decisive influence as regards the delimitation of the belt of sea coming under the immediate jurisdiction of states having an adjacent coastline. The extent of territorial waters was originally determined by technical considerations directly based on the celebrated theory of the Dutchman Bynkershoek concerning the range of a cannon-shot (*De dominio maris,* 1703), which is expressed in the adage *Ibi finitur terrae dominium, ubi finitur armorum vis.* Defined in precise terms in 1782 by the Italian Galiani, who was the first to identify the range of a cannon with the three-mile limit, this criterion replaced, for many years, all previous definitions (median line, line of sight, etc.). The fact that, owing to the advance of ballistics and the development of guided missiles, it no longer corresponds to realities, should not make us forget that for a hundred and fifty years it served as a general standard for determining the extent of territorial waters.

The influence of scientific methods is again perceptible when it comes to fixing the point from which the belt of territorial waters begins, especially in cases where the coastline is not straight but irregular with deep indentations. The two most usual methods—the polygonal plotting and the tangent curve—derive directly from the transposition of geometrical data.

Submarine Tunnels

Advances in scientific technique in our day have given rise to an important problem—that of the extension of the jurisdiction of a coastal state to the bed and subsoil of the high sea. One of the first aspects of this problem relates to the status of any submarine tunnels which might be dug beneath the ocean. No special legal questions are involved when such a tunnel and the two points it links are under the jurisdiction of the same state (as in the case of the submarine tunnel dug during the years 1936 to 1954 between Shimonoseki and Moji, linking the Japanese islands of Hondo and Kyushu, of the proposed submarine tunnels linking the Japanese islands of Hondo and Hokkaido, connecting Sakhalin with Siberia, the Danish island of Saltholm

with Copenhagen, etc.). But matters are different when the tunnel is an international thoroughfare, linking two different states—as with tunnels contemplated under the Bering Strait (between Siberia and Alaska), the Straits of Gibraltar (between Spain and Morocco) and, most important of all, under the Channel (between France and Great Britain).

The idea of linking England to the continent by a submarine tunnel is a long-standing one, since it was put forward for the first time by the French engineer Mathieu, in 1802, just after the Peace of Amiens. It was taken up again in 1838 by Thomé de Gamond, Chief Engineer of the Pas-de-Calais department, who devoted his fortune and his life to it; and yet again, in 1873, by the economist, Michel Chevalier. It was not, however, until after the Franco-Prussian war of 1870 that negotiations were opened between the French and British governments. In two notes, dated 24 June 1872 and 26 December 1874, the British Government expressed, in principle, its acceptance of the project. Exploratory work was even started on both sides, in pursuance of an English law of 16 July 1874 and a French law of 2 August 1875. But the project was finally rejected in 1883, for military reasons, by the special committee which had been appointed by the British the previous year; the same objections were to be advanced later by the Prime Minister, Mr. Asquith, on 21 March 1907.

The question was to be raised afresh after the first world war. But the hopes nourished on the French side were to be disappointed yet again. On 24 July 1924, the MacDonald cabinet issued an official statement to the effect that the objections levelled against the project on military grounds by the Committee of Imperial Defence outweighed the possible advantages of the scheme. The conclusions in favour of the tunnel contained in the report (published on 28 February 1930) of the special committee appointed by the Baldwin government on 5 April 1929, and presided over by Mr. E. R. Peacock, did nothing to alter the situation,[1] any more than the various steps taken since 1945 on either side of the Channel (formation of a British Parliamentary Committee in 1947 under the chairmanship of Mr. Christopher Shawcross; formation of a corresponding group in the Conseil de la République in France; demonstration in London on 11 February 1949 organized by the International Road Federation; tabling of a motion in favour of the project in the House of Commons on 30 March 1949; lecture at the Théâtre Marigny on 11 March 1949 by Mr. Pineau who was the French Minister of Works at the time; approval of the project by the Annual Conference of the International Touring Alliance at The Hague on 28 May 1949), etc. It may be noted that the cost of the tunnel, estimated on the English side at £30,600,000 in 1930 and £100 million in 1948, was put at the closely comparable figure of 90,000 million francs by the French in 1951.

1. In the House of Commons the project was defeated by 179 votes to 172 only.

The latest version of the engineering plans provided for the construction, within a period of eight years, of an exploratory pilot tunnel and two commercial tunnels for an electrified railway. The scheme recommended was that of the Channel Tunnel Co., which was selected in preference to the more ambitious—but prohibitively costly—scheme of London and Paris Railways Promoters Limited. The plan would involve the construction, between Sangatte and Dover, of a tunnel 36 miles in length of which 24 miles would be actually under the Straits, the remaining 12 miles being taken up by underground loop-lines between Bevreguen and Sangatte, and Dover and Sandling Junction.

At the same time that engineers and geologists were examining the technical aspects of tunnelling under the Channel, the jurists were considering its future legal status. As early as 1908, the Frenchman Raymond Robin had concluded that for the construction of the tunnel the consent of the two 'Channel' states only would be needed, and that the question of the agreement of third states did not arise; that half the tunnel should be under British, and half under French, sovereignty, the dividing line being at a point equidistant from the coasts of the two states[1] measured from the low-water mark; and lastly that the destruction of the tunnel by a belligerent in the event of war would be lawful, thus excluding any extension to the tunnel of the provisions of the conventions on neutralization applicable to international canals.

The legal problems were examined at some length in 1930 by the Peacock Committee (paragraphs 140 to 143 of the report quoted above). Its terms of reference being exclusively technical in character, the committee was not required to suggest solutions for the legal or administrative problems. It confined itself to emphasizing the necessity of defining by treaty the interstate frontier within the tunnel and to recommending the adoption of common rules for dealing with offences committed in the tunnel and for the exercise of legislative, jurisdictional, police or customs powers in respect of occurrences inside the tunnel.

Matters are far less advanced as regards the two other submarine tunnels that have been considered. Whereas, for the Channel tunnel, the estimates are ready and the layout has been studied exhaustively—more than ten thousand soundings have already been taken—the state of affairs with regard to the project for a tunnel between Europe and Africa is quite different.

Nevertheless, fairly detailed schemes have already been worked out beginning with the one submitted in 1869 to the Madrid government by the Frenchman Laurent de Velledeuil. Leaving aside the fantastic Gallego Herrera plan—the essential feature of which was a floating tunnel kept in position by a system of moorings—a Spanish ministerial committee, in 1930,

1. A similar view on this point had earlier been taken by the Krantz Report of 1875 and in Article I of the Draft Convention prepared by the Franco-British Committee of 1876 (the frontier in the tunnel to be midway between the low-water marks on the French and English coasts).

decided in favour of the conventional design of a subterranean tunnel on which the 1927 scheme of Colonel Pedro Jenevois was based. After detailed exploration of the structure of the subsoil beneath the sea bottom by the 'shock-wave' method—whereby the rebound of shock-waves from different geological strata is recorded at the surface by electric seismographs—the committee favoured an elbow-bend design, so as to avoid the deepest areas. The proposed tunnel would be 21 miles in length and would link Torre de la Pena, in the Paloma region, 5 miles west of Tarifa, with Rax and Buera, a few miles east of Tangiers in the Punta Ferdigua region. As well as a motor road, the tunnel would include two three-rail railway tracks which could handle either Spanish broad gauge (1.676m) or international standard gauge (1.435m) rolling stock. The cost of construction, estimated by Jenevois in 1927 at 300 million pesetas, would today exceed 1,000 million pesetas, or more than £90 million ($250 million).

Here the legal problems will be much simpler than in the case of the Channel tunnel, as exit and entry will both be in Spanish or Spanish-controlled territory. Hence the probability is that, if the scheme is ever carried out, it will be undertaken by Spain alone. Nevertheless the special legal status of the Spanish zone of Morocco, the fact that Morocco is a single protectorate with France as the only authentic protecting power, and the proximity to one another of a number of territories of varying status (Spain, Gibraltar, Morocco, the International Zone of Tangier) would probably make it impossible to regard the proposed tunnel as an exclusively Spanish undersea route. It is likely that some legal devices would be necessary to take account of the complexity of the surrounding political situation.

Prospecting and Development of Submarine Petroleum Deposits

The extraction of petroleum deposits lying beneath the ocean is the newest branch of the petroleum industry and the first of the marine mining industries. It involves a series of delicate and relatively complex technical operations—first, prospecting to determine the structure and composition of the strata below the sea bed (use of aerial photography for rocks rising near the surface, plotting of magnetic maps of areas of the ocean by means of magnetometers suspended from aircraft or helicopters, possible use of bathyscaphes, direct detection of hydrocarbons beneath the sea by sample borings, etc.); next, exploration drilling (use of improved electrical techniques, construction of artificial islands, etc.); and lastly, production drilling (installation of submarine pipelines, use of anti-corrosion casings, adoption of methods of electrical protection of metal parts, etc.). Only recent technological progress has made possible the use of all these techniques.

Petroleum has already been found below the sea off the coasts of Texas, Louisiana, Mexico and Venezuela, in the Persian Gulf, and off the Tunisian

coast, in the Gulf of Gabès, in the neighbourhood of Djerba and Kerkennah Islands. However in the present state of equipment and techniques, prospecting has not been extended beyond territorial waters. So far the maximum depths at which it has been carried out do not exceed 660 ft, but there is no reason to doubt that the steady improvement of technical resources will make prospecting feasible at greater depths, for which, now that Commandant Houot and Mr. Willm in FNRS-3 have reached the record depths of 13,300 ft, 120 miles off Dakar on 15 February 1954, the bathyscaphe would evidently be invaluable.

All this has immediately given rise to a new legal problem, since the conservation of the mineral wealth of the sea bed and the strata beneath it make it necessary to devise legal means of safeguarding the continental shelf, i.e. the submarine platform or base upon which the continents appear to lie. So far there has been only one instance of a settlement by treaty—the Anglo-Venezuelan Agreements of 19 April 1941 and 26 February 1942 on the exploitation of the petroleum deposits of the Gulf of Paria, between Venezuela and the British island of Trinidad. The 1942 treaty provides for the annexation, by the two states concerned, of the underseas areas delimited under the terms of the Agreement of 1941, the parties having given advance undertakings to recognize each other's acquisitions within the boundaries and on the conditions agreed between them. This double and parallel annexation is clearly based on the concept that outside territorial waters the sea bed is *res nullius,*[1] sovereignty over which can be acquired by occupation. An analogous concept guided the negotiations, mentioned above, between the French and English governments relating to the construction of the Channel tunnel.

In most cases, the legal regulation of these questions has been of an internal character, the majority of the countries concerned having preferred unilateral regulation, on the model of the United States of America whose jurisdiction over the natural resources of or beneath the continental sea bed contiguous to the American coast was extended beyond the three-mile limit by the Presidential Proclamation of 28 September 1945. In interpreting the Proclamation, American case law laid it down in the first place, by the Supreme Court decision of 5 June 1950, that the Federal Government had paramount rights over the continental sea bed overriding those of the particular coastal states concerned, in this case Texas and Louisiana. However, a subsequent Act, the Submerged Lands Act and Outer-Continental Shelf Act of 22 May 1953, conceded the rights of coastal states over the adjacent maritime areas, while establishing a reserve of crude petroleum for the needs of national defence, and for the U.S. Navy in particular.

1. That is, a thing belonging to no one, in contradistinction to *res communes* which are common property.

Since 1945, the lead given by the great North American republic has resulted in a whole series of analogous decisions by the states of Latin America (Mexico, the Argentine, Nicaragua, Chile, Peru, Costa Rica), by Great Britain (for Jamaica and the Bahamas), by the states of the Persian Gulf (Saudi Arabia, Kuweit), by Iceland, by the Philippines, by Pakistan and by Australia. There exists, however, a notable difference between the North American proclamation, which goes no farther than regulating and controlling exploitation without excluding participation by third states, and the measures adopted by the Latin American republics and by Australia—the last-named under the Proclamation of 11 September 1953—which in some instances extend their *sovereignty* up to 200 miles seaward over the areas of the high seas which they reserve the right to delimit.

In this connexion, in 1951, the International Law Commission of the United Nations conceded that control and jurisdiction over the sea bed and subsoil in areas outside territorial waters could be exercised by the coastal states for the purpose of prospecting and exploiting the natural wealth contained therein, but subject always to there being no 'undue interference' with other states' freedom of navigation and fishing. In a recent arbitration award,[1] the view was taken that the draft regulations in question did not reflect the existing state of the law and that the concept of the continental shelf could not be cited by a company holding a petroleum concession granted in 1939, at a time when this concept was 'barely known in international law'.

The Legal Status with Regard to the Atmosphere and the Stratosphere

A brief mention only will be made here, as a reminder, of the influence on international law of technological progress in the sphere of aeronautics since the beginning of the present century. The phenomenon merits some attention because it provides revealing evidence of the traditionalism which still plays a considerable part in shaping the law of nations. Whereas one might have expected that an international air law would be drawn up, free of nationalistic prejudices and based on the right of all men to the use of air space, it must unfortunately be recognized that in this domain the development of legal speculation has not kept pace with that of scientific discovery.

The first authorities to tackle the problem almost always tried to transfer to air traffic the principles applicable to maritime navigation, ascribing to each state exclusive jurisdiction over the air space immediately above it, by analogy with the traditional theory of territorial waters. And when positive law came into evidence after the first world war, we find the Convention of

1. Arbitration award made in November 1951 by Lord Asquith of Bishopstone between the Sheikh of Abu Dhabi, on the Trucial Coast, in the Persian Gulf, and the British Petroleum Development Company, on the applicability to that company of the sheikh's proclamation of 10 June 1949, extending his authority over the submarine plateau adjacent to the territorial waters of Abu Dhabi.

Paris of 13 October 1919, undeterred by the pleonasm, asserting emphatically 'that each power has complete and exclusive sovereignty over the atmospheric space above its territory'. Some states, including France, at once inferred that the air space above their territory was part of their public property.

The conquest of the stratosphere, following upon the flights of Professor Picard, and of Prokofiev and Ussienko, led jurists to consider the legal position regarding stratospheric space. For broaching the question, as early as 1934, credit must go to the Soviet professor Korovin. However, the conclusion he reached—the need to extend vertically the boundaries of state sovereignty—is rather disappointing, since it assumes that there will be identical regulations for the atmosphere and the stratosphere without a height limit. Here again the discrepancy between the boldness of the stratospheric navigators and the timidity of the jurists is appreciable.

Regulations concerning Radio-Communication and Broadcasting

Questions relating to air transport and the legal status of aircraft are not the only ones arising out of the use of the air. Wireless telegraphy, by the emission through space of electromagnetic waves, could not fail to attract the attention of the jurists. In this connexion, problems arise which call in question the very rights of a state pertaining to the air space situated above its territory: the right of a state to emit, in its own territory, Hertzian waves directed towards another state; whether a state lying between the transmitting and receiving states can object to the passage of the waves over its territory in transit, etc.

Only with the International Radiotelegraphic Convention of Washington, of 25 November 1927, was any appreciable progress made in the matter, since the terms of reference of the earlier conventions concluded at Berlin on 3 November 1906 and in London on 5 July 1912 were confined to maritime radio-communications. The general regulations adopted in Madrid on 9 December 1932 completed, on the technical side, the work of the earlier conventions, by laying down rules for the choice of apparatus, the quality of transmissions, the use of frequencies, interference, etc. Later, other international agreements, at Geneva in 1951 and at Buenos Aires in 1952, brought the legal status of radio-communication into line with the unceasing progress made on the technical side.

A distinction should be drawn between radio-communication and broadcasting, in which the waves are not directed but are picked up by any station capable of receiving them. Following preliminary legal studies, there have been several conventions during the last quarter century (at Prague in 1929, at Lucerne in 1933, at Cairo in 1938, at Montreux in 1939, at Atlantic City in 1947) to co-ordinate the activities of the various broadcasting stations by

sharing out the wavelengths among them and allotting each a specific wavelength. The current convention, which has been in force since 15 March 1950, is the one signed at Copenhagen on 15 September 1948.

The distribution of wavelengths between European broadcasting stations —310 in 1939 and 415 today—has presented the engineers with delicate problems: given the desirability of a minimum difference of frequency of 9 kilocycles (9,000 vibrations per second) between one station and the next to avoid their interfering with one another, the total of the frequency bands set aside for, or usable by, broadcasting, which amounts to 1,160 kilocycles, enables only 130 exclusive wavelengths to be distributed. For these, there were 310 candidates in 1939 and 415 in 1948. It was through technology that the necessary adjustments were made. Indeed, it was impossible to allocate a wavelength of its own to every transmitting station, but it was not an absolute technical necessity that each of them should have an exclusive wavelength. The fact is that not all transmitters are, like the strongest stations, of 100 kW power; their effective range is therefore variable. Moreover, each state has not enough broadcasting material for every one of its broadcasting stations to be able to claim the right to send out an exclusive programme every day of the year.

The European delegates therefore devised several types of wavelength—shared wavelength (i.e. a wavelength used by two or more stations in different countries); international common wavelength (which can be used by an unlimited number of stations belonging to different countries which do not exceed 2kW in power), and the national common wavelength (which may be defined in the same way except that it is an internal matter for a given state). The delegates also accepted the principle of synchronized stations, i.e. two or more stations in the same country normally transmitting the same programme on the same wavelength; this is the price to be paid for the prodigious growth of broadcasting, but it is largely offset by the excellent quality of the broadcast.

MODIFICATIONS IN THE EXERCISE OF JURISDICTION

Less spectacular are the modifications which technological progress has brought about in the regulations for the exercise of state jurisdiction under international law. However, the very fact that this phenomenon has become commonplace makes it all the more revelatory of the influence exercised on the evolution of the law of nations by scientific discoveries.

Thus, in the exercise of its proper jurisdiction, each state is finding it necessary to take into consideration the interests of other states, particularly those bordering on it. If neighbourship creates rights, it also imposes obligations.

In the matter of riparian rights, watercourse development for the generation of hydroelectric power has led to the conclusion of bilateral or regional agreements to secure the rational exploitation of waterways in which adjoining states have an interest. So far most of the agreements of this type have been between European states (Franco-Swiss Convention of 4 October 1913 on the development of the water power of the Rhône, Franco-Italian Convention of 17 December 1914 regulating the use of the waters of the Roya, Spanish-Portuguese Convention of 11 August 1927 on the Douro, Austro-Yugoslav Agreement of 13 March 1952 on the Drave, etc.). On more general lines, the Geneva Convention of 9 December 1923, drafted under the auspices of the League of Nations, lays down the conditions governing the harnessing of hydraulic power in which a number of states have interests (construction, maintenance and operation of the works, financial co-operation, technical supervision, provisions for the maintenance of public security, conservation of the sites, protection of the rights of third parties, settlement of differences, etc.).

On the American continent, progress has been slower. Thus the harnessing of the St. Lawrence was long delayed by the resistance of the American Senate, which successively rejected the two Treaties of 18 July 1932 and 19 March 1941 concluded to that end between the United States of America and Canada. It was only recently, in May 1954, that Congress finally authorized the American Administration to undertake, jointly with the Canadian Government, the construction of the St. Lawrence Seaway which is expected to make the St. Lawrence the principal artery of North American commerce and, by the installation of dams and hydroelectric plants with a capacity of 2,600 million kWh at Massena and Ogdensburg, to transform the economic life of this part of the continent while making the St. Lawrence navigable from the Atlantic to the Great Lakes. There is room for endless discussion about the sociological consequences of an undertaking which may perhaps in the near future convert Chicago, hitherto one of the bastions of isolationism, into a seaport.

On the southern frontier of the United States of America, on the Rio Grande, the inauguration, on 19 October 1953, after 22 years of negotiations, and five years of building operations, of the Falcon Dam by Presidents Eisenhower and Ruiz Cortinez was an outstanding event in the history of the international regulation of hydroelectric power. This gigantic piece of engineering, which will generate 250 million kWh per year, is the first of a series of three dams, the construction of which as a joint undertaking was provided for under a special treaty between the United States of America and Mexico.

We cannot leave the subject of electrical power without mentioning that the transmission of current in transit—regulated by the Geneva Convention of 9 December 1923—and arrangements between neighbouring states for

the disposal of surplus power (arrangements already exist between France and Germany and are likely to be made in the near future between France and the United Kingdom and between Canada and the United States of America) give rise to conventions on the sharing of electrical power, thus opening new vistas for the regulation of international relations.

In maritime matters, the formulation of the recent theory of the continental shelf has provided an opening for establishing the jurisdiction of coastal states over submarine petroleum deposits, subject to the legitimate reservation of non-interference with the customary fishery and navigational rights of third states.

In the matter of air transport, there has been a similar reconciliation of the rights of the subjacent state and of third states, respect for the sovereignty of the former having necessarily to be combined with the maintenance of a right of way for all the others.

The traditional counterpoise to a state's independence in international matters is its liability when, in the exercise of its sovereign powers, it causes damage to third states. By expanding the category of unlawful acts, scientific discoveries have furnished added occasions for confirming the validity of this general principle.

In the territorial sphere, the rule whereby all states are required to refrain from acts liable to cause damage in the territory of neighbouring states has been confirmed by international jurisprudence in circumstances of some technological interest. The decisions in point are those delivered on 16 April 1938 and 11 March 1941 in the matter of industrial fumes from the Trail smelting plant by the special arbitration tribunal between the United States of America and Canada set up by the compromise of 15 April 1935. Trail is in British Columbia about halfway between the Pacific and Alberta and is the site of a large zinc and lead smelting works about seven miles from the international frontier between Canada and the United States of America. The smelting process causes the release of large quantities of sulphur dioxide fumes which are discharged from the works' chimneys and may—in certain atmospheric conditions—be carried by the wind across the frontier. These fumes cause damage to crops and vegetation in the frontier areas on the American side of the line. The tribunal ruled that Canada was liable and accordingly awarded damages to the government of the United States of America. The principle is, after all, a commonplace in internal law—in France, particularly, administrative case law has long worked on the classical theory of the liability to pay compensation for damage of this character, due to abnormal risks deriving from proximity of public works—but it had never previously been stated so specifically in international relations.

As regards waterways, modern techniques for the collecting and conveying of waters may likewise result in a liability being incurred by a state carrying

out such works when they affect the flow of a frontier river or an international watercourse and, hence, infringe the rights of the other riparian state. The question was raised in 1937 before the Permanent Court of International Justice in the matter of diversions from the Meuse, the point at issue being whether certain development works carried out by the Belgian and Dutch governments (particularly on the Zuid-Willemsvaart and Hasselt Canals, on the Bosschveld lock, etc.) were compatible with the provisions of the Dutch-Belgian Convention of 12 May 1863. In its decision of 28 June 1937, the Permanent Court nonsuited both parties, finding that neither state had violated the Treaty of 1863. This, however, was the decision on one specific case and the possibility remains that, in different circumstances, a political organ or arbitration tribunal might find the riparian state liable. A similar dispute between Syria and Israel has been before the Security Council since last autumn, Israel being accused of diverting the waters of the Jordan for its own exclusive benefit and of seeking to make that river exclusively Israeli, in violation of earlier international agreements.

The question is not a simple one and jurisprudence itself has not so far contrived to work out an answer unanimously accepted, at any rate as regards the related problems of the diversion of underground water and the collecting of springs. With reference to the first, especially as regards the diversion of underground seepage, most authorities tend to accept the principle of the freedom of action and sovereignty of states in respect of the subsoil of their own territory. As regards springs, the law is ambiguous. In the past the question has been raised as to whether it was legally permissible to cut off, in Austrian territory, a radioactive spring located at Brambach, near the Austro-German frontier. Perhaps, as the Yugoslav jurist, Professor Andrassy, of the University of Zagreb, has suggested, a distinction should be made between springs gushing out naturally and those obtained by well-drilling, special legal regulations being appropriate in the latter case.

In an analogous connexion, the discoveries of speleologists may give rise to similar difficulties. A case in point is that of the expedition undertaken last summer by French speleologists in the Pierre Saint Martin Caves, when Spanish authorities lodged an anticipatory objection to any diversion of the subterranean watercourses, over four miles in length, liable to threaten a reduction in the volume of water flowing to the Spanish side. Under the terms of the agreement reached on 4 August 1953 between representatives of the two states at the international railway station of Canfranc, it was agreed that a new water colouring test should be carried out with fluorescein to determine whether the underground river feeds the streams of Navarre, in which case the supplies are to be divided between the two countries in proportion to the volume of the streams on either side of the frontier.

Maritime matters likewise have not remained unaffected by scientific discoveries prejudicial to the rights or interests of third states.

Pollution of the Sea by Oil

An outstanding question for nearly 30 years past has been to find means of preventing, by suitable international regulations, the discharge of fuel oils or oil mixtures on the high seas by motor vessels or tankers with consequent pollution of the coastal areas, for, in certain conditions of wind and tide, pollution may occur at considerable distances from the point of discharge.

This is a many-sided question. The pollution of the sea itself by petroleum oils leads, in the first place, to the destruction of sea birds (gulls, petrels, albatross, etc.) by soaking their wings with oil, leaving them quite incapable of swimming, flying or diving and often doomed to a slow and painful death by starvation. Oil pollution of the sea likewise brings with it the destruction of fish, shell-fish and the marine vegetation which is the chief food of fish and sea birds. Pollution of the beaches is a nuisance to bathers, causes financial loss to watering-places and is a danger to public health. Lastly the accumulation of petroleum oil, which is often liable to be carried by the current from outside territorial waters right into seaports, creates a definite fire risk. All countries suffer to a greater or lesser extent, those most affected so far having been Great Britain, the United States of America, Japan, and to a lesser degree Denmark, France and Italy.

A conference met at Washington as early as 1926 to consider the problem and worked out a draft convention which unfortunately was never ratified. Therefore, in July 1934, the British Government asked the League of Nations Organization for Communications and Transit to reopen the question with a view to the conclusion of an international convention. A committee of experts, convened at Geneva for the purpose between 19 and 23 November 1934, favoured the suggestion. A remedy which would be wholly effective appeared to be difficult to achieve as pollution may arise from shipwreck or collision at sea or from the deliberate discharge of petroleum onto the surface of the sea in heavy weather or to assist other vessels in distress. These were causes of pollution which none of the possible measures would remedy. However, prevention of the pollution arising from the deliberate discharge of oils or oil mixtures by ships on the high sea could have been achieved by the joint action of the principal maritime powers.

But the second world war broke out before the international conference proposed in 1934 and accepted in principle in a number of resolutions voted between 1935 and 1937 by the various organs of the League of Nations (Council, Assembly, Advisory Commission on Communications and Transit) could be convened. The problem is not less acute than it was, as is shown by a recent motion signed by 16 Members of Parliament and tabled in the

House of Commons on 14 November 1952 asking the British Government to take all practicable steps to avoid the persistent pollution of the coastal waters of Wales through fuel oil discharged from certain vessels, by drastically prohibiting any discharge of industrial fuel oils within an adequate zone surrounding the British coast.

The following year, in October 1953, representatives of eight states and unofficial observers from 26 others met in private conference in London. On the whole, this conference concurred in the proposals put forward previously by a committee under the chairmanship of Mr. P. Faulkner on the prevention of the pollution of the sea by petroleum oils. The Faulkner Report recommended the prohibition of all discharge of mineral oils within an area including the Faroe Islands, the North Sea and the Bay of Biscay and extending to a line about 2,000 miles westward and south-westward of the British Isles. These recommendations go much further than the prohibition —in force since 1922—of the discharge of mineral oils within three miles off the coast, and than the voluntary undertaking of 1926 by the shipowners of a number of countries to refrain from discharging heavy oil within a minimum distance of 50 miles from the coast. However measures as Draconian as those proposed in 1953 were and are necessary, since the area of pollution has recently spread as far as the Antarctic Ocean, covering seals with a thick coat of oil waste and tar, and condemning penguins to a slow death. It is to be hoped that the international agreement on pollution signed in London on 12 May 1954 will have brought to a conclusion a discussion which has dragged on all too long.

Guided Missile Tests

The customary principle of the freedom of the seas, though justifying the use of the high seas by all states for economic purposes, especially those relating to fishing and navigation, is against the use of ocean areas, in time of peace, for firing tests which may cause danger to third parties. At the very least, the consent of these third parties must first be obtained through the usual treaties.

In 1949, the United States of America announced that they proposed to construct a launching site for guided missiles with a range of 3,000 miles in a south-easterly direction (i.e. in the direction of the Bahamas, the Virgin Islands, Guadeloupe and Martinique), in the Banana River region, on the east coast of Florida, near Cape Canaveral. Although it was stated that the missiles would not contain explosive charges and would be equipped with a special device to ensure that they remained under control in flight, it may be asked whether such tests, when conducted above the Atlantic outside the territorial waters of the state concerned, do not infringe the principle of the freedom of the high seas, by causing danger to the peaceful shipping of other

powers. The French West Indies are scarcely more than 1,500 miles from the launching point of these missiles, and in their direct path.

However this may be, the United States of America concluded three agreements, with Great Britain—dated 21 July 1950 and 15 January 1952—and with the Dominican Republic—dated 26 November 1951—giving them the right to carry out tests with guided missiles in the region of the Bahamas and the West Indies. However, such agreements obviously cannot be cited against other states, since, by the accepted principles governing the application of treaties, bilateral undertakings cannot have effect on any but the contracting parties. The first experiments in the launching of missiles by pilotless aircraft were actually made at Cocoa, on 21 June 1951, over the stretch of sea between Florida and the Bahamas.

The advisability of drawing up suitable legal regulations is clearly apparent when it is recalled that, at a press conference on 16 January 1953, Mr. Thomas Finletter, then U.S. Secretary of the Air Force, stated that his country would 'fairly shortly' possess a guided missile capable of being aimed accurately at an objective on the other side of the Atlantic. A few days earlier, on 10 January 1953, the Boeing Airplane Company had disclosed that, as early as 1949, it had perfected a missile capable of attaining a speed almost twice that of sound. In these circumstances, it can be seen how out of date is the criterion of cannon-shot range once laid down by Bynkershoek to define the extent of territorial waters.

Atomic Tests

The same principles apply with regard to compensation for damage caused on the high seas by atomic tests. As is generally known, at the time of the H-bomb tests carried out by the American Government on 1 March 1954, 70 miles to the west of the Eniwetok-Bikini atoll in the Marshall Islands, 23 Japanese sailors belonging to the fishing-boat *Fukuryu Maru*—who were outside the forbidden area—were seriously burnt by radioactive dust resulting from the explosion of the hydrogen bomb. The American authorities have agreed spontaneously to compensate the victims. All the same, there are at present no international regulations governing such tests. The fact that they are carried out in territories under strategic trusteeship, and therefore practically outside the control of the United Nations, makes it still more advisable that suitable regulations be drawn up. Some experts have, in fact, pointed out that any power, after taking the necessary precautions and warning the parties concerned, can carry out any tests it likes on the high seas. Others have drawn attention to the fact that, at the present time, with the growing power of the devices being tested, it is difficult to foresee exactly how far the repercussions of explosions may make themselves felt. To what extent is any one country entitled to experiment with bombs whose exact

power is unknown and whose effects may one day be felt in other countries thousands of miles away? This question has still to be answered.

So far, the ill effects of scientific progress have been less serious, in time of peace, as regards *air matters*. But they still deserve mention.

The War on the Air

Indeed broadcasting, which in all countries is either guided by governmental directives or subject to state control, constitutes, in the very nature of things, a delicate problem. It cannot, like the press, be stopped at the frontier. It is addressed to listeners in all countries and, very often, in their own language so as to reach them more easily. Before the *Anschluss,* people in Austria listened to the Munich broadcasting station and people in Germany to Vienna, and all remember the part the Munich broadcasts played in the Austro-German tension which led up to the abortive rising of 25 July 1934. At the beginning of the second world war, Radio Stuttgart broadcast propaganda programmes in French. From 1940 to 1945, the BBC was the very soul of the European resistance to Hitler's totalitarian imperialism. Music itself, in some cases, may have a propaganda value: the *International,* broadcast by the Russian stations, was for a long time considered revolutionary in the West. The fascist government denounced as seditious the song of Andreas Hofer, the hero of the Tyrol, and the Spanish Republican Government at one time prohibited the singing or playing in Barcelona of the Catalan harvesting song. What is more, silence itself may be a source of conflict, since in 1934 the government of the Netherlands forbade a broadcasting company to observe one minute's silence in its programmes in commemoration of the tenth anniversary of the death of the Italian socialist leader, Matteoti, who was assassinated under the fascist régime.

There have even been some diplomatic incidents, such as that of the BBC broadcasts on New Year's Day, 1933, which contained some comments on domestic policy and called forth protests from the Italian and Polish governments, or the Italo-Belgian incident of 4 October 1935 (following a broadcast from the Italian radio stations contesting the facts of the German atrocities committed in Belgium in 1914), or again the protests of the British Government against the anti-British propaganda broadcasts by the Italian stations in the Middle East during the autumn of 1935, and the recent protests of the French Government (March 1954) against certain Egyptian broadcasts in Arabic intended for North Africa, etc.

It is therefore understandable that a convention should have been concluded, on 23 September 1936, under the auspices of the League of Nations, on the use of broadcasting in the interests of peace. Under the terms of this convention, which was signed by 28 states, and came into force on 2 April

1938 as between six of the signatories, governments undertook to prohibit on their respective territories any broadcast inciting the inhabitants of a foreign territory to acts incompatible with domestic peace or public security. They undertook to ensure that broadcasts transmitted by their countries should constitute neither an incitement to war nor provocation likely to lead to war, to prohibit any broadcast likely to harm good international understanding by inaccurate statements, and to check the accuracy of information broadcast about international relations, particularly in time of crisis. A fine programme, which it would be invidious to compare with the reality of the years that followed.

The war on the air has taken a more insidious form in recent years through deliberate 'jamming' with the object of interfering with the broadcasts of certain foreign stations. Such incidents have frequently occurred, for instance, between the United States of America and the Soviet Union, the Russian-language propaganda broadcast entitled 'The Voice of America' having been systematically jammed by the Soviet stations since February 1948 to prevent it from being heard by listeners in Eastern Europe. An official protest about this was made by the American Government to the International Telecommunication Union on 2 May 1949.

The general question of the jamming of radio transmissions was discussed in the United Nations by the Sub-Commission on Freedom of Information and of the Press at its Fourth Session in May 1950. The sub-commission adopted a draft resolution condemning the Soviet Union for deliberately interfering with the reception by the people of the U.S.S.R. of certain broadcasts transmitted from sources outside the territory of the U.S.S.R. The General Assembly of the United Nations, at its Fifth Session, in turn adopted a resolution, on 18 November 1950, condemning interference with foreign broadcasts as an infringement of the right to freedom of information. It may be mentioned, incidentally, that Article 19 of the Universal Declaration of Human Rights, dated 10 December 1948, endorses the right to listen freely to radio broadcasts, regardless of their source, and that, according to Article 44 of the International Telecommunication Convention, all stations must be established and operated in such a manner as 'not to result in harmful interference to the radio service or communications of other members'.

It must, unfortunately, be admitted that in this sphere state sovereignty is particularly jealous of its prerogatives. It will be remembered that in France a few years ago the *Tribunal des Conflits,* at the suit of the French Broadcasting Company against the Board of Management and Publicity of the Radio Andorra Station, by a decision of 2 February 1950—taken incidentally in spite of the plea of the Government's Commissioner—ruled that the order to jam the broadcasts of Radio Andorra, given to the Director-General of the French Broadcasting Company through the appropriate ministers, was of such a nature as to remove it from the jurisdiction of any tribunal, and

came within the category of 'acts of government' against which there can be no remedy at law.

Artificial Control of Rainfall

The exercise of state sovereignty in the air may be affected by the artificial production of rain. The problem consists in bringing about a disturbance of the colloidal stability of the cloud before this would occur in the natural order of things. When more is known about the releasing of artificial rain, it may even be possible to produce the cloud itself.

Experiments along these lines were made in the Netherlands as early as 1930. But it was not until after 1949 that extensive and systematic research was really undertaken in the English-speaking countries (United States of America, Australia and Canada). The method in most common use is to introduce into the clouds, by aerial seeding, particles which bring about the formation of ice. Silver iodide crystals and solidified carbon dioxide are used for this purpose, the particles of dry ice being sprayed from an aeroplane flying either above or in the cloud.

The problem is beginning to occupy the attention of official circles, both national and international. In the House of Commons, on 24 February last, the question was brought up by Mr. de Freitas, a Labour member, although only the domestic legal aspect of the possible consequences of such experiments seems to have been considered by the Parliamentary Under-Secretary of State for Air, Group Captain Ward. In a study published in March 1954, the Secretariat of the World Meteorological Organization gave particulars about the results of a preliminary enquiry into experiments on the 'artificial inducement of precipitation'—as it is officially called—so far carried out, particularly with reference to the arid and semi-arid regions. This shows that the results so far achieved are inconclusive: neither the complete failure of the methods employed nor the certainty of getting substantial increases of rainfall has been demonstrated. The most that can be said is that the most favourable conditions for the artificial inducement of precipitation are to be sought in regions and during seasons where natural precipitation is most likely. The methods at present used bring about only a very small increase in precipitation in arid or semi-arid regions, or during dry periods in regions of normal medium rainfall.

But, as the possibility of producing rain artificially does undoubtedly exist, we must now begin to consider its consequences from the standpoint of international relations. In particular, it must be recognized that a state can cause rain to fall on its territory by breaking up clouds which, without this artificial intervention, would have shed their water content on the territory of a neighbouring state. There is thus a danger that, during periods of drought, each state might try to capture as much rainfall as possible, thereby depriving its

neighbour of the benefits of natural rainfall. Should it then be concluded that states should be legally obliged, by agreement, to refrain from any action likely to alter the normal and natural course of meteorological phenomena to the detriment of other states?

APPLICATION OF THE LAW OF WAR

The implications of scientific discoveries have been mainly considered in relation to the law of war. But from the point of view of international law this is of real interest only to the extent that legal regulations are directly affected. In this respect—to give only a few examples—neither the invention of the arquebus or the mortar, nor the improvement of armour, nor the use of automatic weapons, torpedoes or contact mines provoked any far-reaching changes in the law of belligerency. Attention will therefore be confined to those technical changes which have brought about, or are likely to bring about, radical changes in the application of rules of law.

The law of *land warfare* has not been seriously affected since 1914 except by the use of long-range heavy artillery. The whole body of regulations contained in The Hague Conventions of 1907 are in fact based, as regards bombardment, on the distinction between defended towns and open towns, only the bombardment of the former being permissible as a counterpoise to their capacity for military defence. This distinction, based on an out-dated method of conducting warfare and devised during the period of mobile warfare, no longer bears any relation to the facts. Even in 1914, it proved impracticable when the front became stabilized as a consequence of trench warfare. The development of guided missiles is also likely to lessen the force of this distinction.

Mention must likewise be made of the far-reaching changes introduced into the law of *sea warfare* by the use of the submarine. After the second world war, it is not too much to assume from these changes that such traditional institutions as the blockade and the right of capture are likely to undergo radical modifications.

The form of naval operations in modern times has indeed considerably reduced the efficacy of blockade, as the risks of submarine attack prevent the blockading squadron from maintaining station before the blockaded port. This accounts for the decline of the blockade during the two world wars. While there were only about ten instances of genuine blockades[1] by the Allies during the 1914 War (blockade of the Austro-Hungarian coast, of the

1. The only measures to which the term 'blockade' can properly be applied are those entailing the prevention of communication between the enemy coast and the high seas by the presence of an adequate naval force. These blockades must be distinguished from the 'quasi-blockades' of the Allies during the first world war and, more generally, from the various measures directed against enemy maritime trade to which the press has applied the technically improper term of 'blockade'.

Greek and Bulgarian coasts, of German East Africa, the Cameroons, Kiaochow, Syria and Asia Minor), there were even fewer blockades during the second world war, almost the only instances being the blockade of the Finnish coasts by the U.S.S.R., and of Hong Kong and Java by Japan.

However, it is the rules governing the capture of ships at sea which have been most affected by technical developments, since attacks against, and the sinking of, merchant ships without warning by belligerent submarines have ousted the classic procedure of boarding and search at sea. The special features of the submarine make it impossible for it to conform with the rules governing the right of capture with regard to warning, search and rescue of the crew. As it has no room to accommodate the crews of ships it has sunk, the submarine naturally tends to launch its torpedoes without warning while remaining submerged, and therefore cannot carry out search. Unlike surface craft, the submarine cannot easily observe the usual rules relating to the right of capture. If it is to call upon a ship to heave to, the submarine must surface, which immediately places it in danger if, for instance, its adversary is an armed merchantman. If it is to search, it needs some craft which may have to be launched in a choppy sea or a slight swell, and it has nothing of the sort. Lastly, if it is to save the crew of the merchantman, it must either take them on board itself—which is scarcely ever possible—or arrange for a captured cargo boat to follow it and pick up the crew—a procedure which is generally impracticable. This line of argument was often advanced and repeatedly developed by the allied and neutral powers during the first world war.

Despite rare precedents, such as the stopping of ships by certain German 'submersible cruisers' of 1,700 tons in 1917, and the famous episode of the French submarine *Poncelet* at the beginning of the second world war (capture of the German steam-ship *Chemnitz* in the South Atlantic on 28 September 1939 and escort of the prize to Casablanca on the following 3 October), submarines can operate against enemy or neutral shipping only by destroying it. This means that, in future, the captor can safely exercise the traditional right of capture only in harbour, forced deviation taking the place of visit and search at sea.

It is scarcely necessary to point out that the development of *air warfare* has practically done away with the distinction between combatants and non-combatants, which was also a feature of a legal situation that is now out of date. The concept of military objective, which in the view of the committee of legal experts meeting at The Hague in 1922-23 provided a means of regulating the use of the air arm, has proved quite useless, for, as Sir Winston Churchill is said to have remarked in 1942, 'civilian morale is also a military objective'. The introduction of chemical and bacteriological warfare and, above all, the development of atomic weapons, are likely to have similar consequences but, this time, on an unlimited scale.

These few observations cannot be said to exhaust the problem. Attention has deliberately been confined to the present, without attempting to anticipate the future developments which some bold spirits have already visualized or prophesied. It is quite clear, for instance, that the establishment of floating islands, the construction of artificial satellites, space platforms or inter-planetary mirrors—as recently announced by Dr. Lincoln La Paz, of the University of New Mexico, and Professor Hermann Oberth, the inventor of the V-2 rockets—may give rise to problems undreamt of today. The inter-planetary mirror, in particular, 60 miles in diameter and facetted to catch the sunlight and reflect it onto the earth, would make it possible to improve the climate of cold regions and render them fertile, but it would also enable us to destroy whole towns or armies by concentrating the heat of the sun on a particular part of the earth's surface, where the temperature would rise to 300° C. The investigation of new sources of power, the use of nuclear energy, the organization of interstellar travel and the possibility of establishing military bases on satellites gravitating around the earth or on platforms built with materials from the earth must henceforth be considered. It will be the responsibility of the jurist to evolve new regulations for these new situations. At this stage in scientific progress, however, the very term 'international law' will be too narrow. So far, indeed, all the legal systems devised by men have been designed for the Earth, that is to say, for one particular planet. But from now on we must accustom ourselves to the idea that the international law of tomorrow will no longer be concerned solely with inter-state, but with inter-planetary affairs.

THE HUMAN ELEMENT IN THE APPLICATION OF SCIENCE

by

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The fascination of the direct and broad impact of science and technology for students of society has tended to obscure the extent to which the day-to-day steps of scientific and technological progress are affected by human and social factors. This aspect is treated here, therefore, from the standpoint of those who have operational responsibility for the application of new scientific and technical knowledge rather than from the angle of the student of society. It concerns the scientific administrator and the industrialist more than the academic sociologist and the anthropologist. The primary aim is to consider how the human element affects the work of those responsible for getting science and technology applied, and the extent to which policies and practices might be changed to cope with the human problem.

THE OPERATIVE FACTORS

Any acceleration of the rate at which scientific and technical knowledge is applied in industry depends on a variety of factors. The relative importance of these factors, and ways and means of overcoming obstacles, have lately been the subject of much discussion and debate. Attention has been drawn to the need for increasing the number of trained scientists and technologists and using them more on the boards of management in industry. The need for governments to take a hand in providing risk finance for the development of new products and processes has been recognized. Links between industry and science have been strengthened through the growth of operational research and technical liaison services at the industrial research associations, thereby ensuring that research bears more directly on production problems.

The influence of all these factors on the rate at which science is applied is indisputable, but experience has shown that, at various points in the chain between the laboratory and the market, the 'human problem' becomes important. Since the first operation required in the application of science is to

get information from the science-producers to the science-consumers, it is convenient to start our discussion of the human factor here. The problem of getting scientific and technical information used in industry is largely one of organizing the traffic, especially in the 'laboratory' or science-based industries. The right channels have to be located, and the load and kind of information they will carry have to be determined. This is largely a question of the mechanics of organization. But the human factor enters in two ways: first, the information transmitted has to be understood; second, it has then to be acted upon. The first of these problems has led to considerable interest in methods of presenting scientific information, and to the growing realization that potential users are being lost because of unnecessary jargon as well as inherent technical difficulty. Indeed, there are some signs that 'prose engineering', which involves using statistical yardsticks of 'reading difficulty' as a means of ensuring that reports are written down to the level of potential audiences, is spreading to the writing of scientific reports. There are a number of limitations to the use of 'prose engineering' in the scientific field, but the most important one is that the impact of a scientific report depends much less on the report itself than on conditions quite external to it—for example the way it is launched, the status and reputation of the organization launching it, the existence of a recognized need for improvement in the field in question. In particular, if the report is to lead to action and implementation, attitudes and climate of opinion are of vital importance. Indeed, there is a growing backlog of applicable information, but even where knowledge, finance and technical skill are available, the vital spark leading to interest and action is often lacking. It is this recognition of the need to persuade reluctant users to take action, to overcome attitudes of indifference or hostility, that has led research organizations to use increasingly the techniques of publicity and public relations.

THE TECHNIQUES OF PERSUASION

If potential consumers and users are ignorant of or hostile to the possible applications of science, then something must be done to rouse their interest and persuade them. Research organizations have therefore—perhaps unwillingly—turned more and more to the publicist for assistance. The tricks and techniques of modern publicity and propaganda have been added to the more austere methods of communicating the results of scientific research. The popular press is in regular and daily contact with government research centres. Even the strip cartoon has made its debut as a means of familiarizing householders in the United Kingdom with research on domestic fuel consumption. Government research organizations use radio, television and the film as a means of arousing interest in their results.

It will help to place the use of these techniques in the right perspective if we focus our attention for a moment on the users of research. It is possible, by drastic over-simplification, to identify three types of situation. First, one in which the users are continually on the look-out for information relevant to their scientific and technical needs. For such groups of users, for example in the science-based industries with numerous scientific staffs of their own, the task is largely one of organizing efficiently the traffic of information. Second, there is the situation in which the prime need is to attract widespread attention to new techniques or to methods not requiring any radical change in existing practice; this would apply to fields where there is an unorganized corps of scientifically-trained professional users, e.g. doctors, sanitary inspectors, architects, etc. Here the usual technique of publicity is what is most required. Finally, there is the situation in which the critical obstacles to technical and scientific advance are traditional attitudes and deeply-rooted practices.

The human element looms largest in this third type of situation; and it occurs not infrequently because technical and scientific developments depend for their success on major changes in ideas and behaviour. For example, the use of plastics in engineering is to some extent inhibited because engineers find it difficult to conceive of plastic structures, with their apparent fragility, taking really large loads; the whole business feels subjectively wrong to them.[1] Any major innovation is likely to run into similar obstacles. The use of automatic control techniques in industry is another case in point; here a quite new approach to product design and production organization is essential. Very much the same applies to scientific developments requiring radical changes in consumer behaviour. The examples in this field are legion: the Britisher's firm insistence on a form of domestic heating that squanders the most precious of the nation's natural resources; the motor-cyclist's refusal to wear a crash helmet despite the eloquence of the official statistics; hinderance to the development of new fibres because of uncertainty about consumer reaction to clothing made from them; etc. One wonders what will be the fortune of micro-biological food products if and when they reach the consumer.

The Inadequacy of Propaganda Techniques

Since technological change and the application of science so often depend on changes in attitude and behaviour, one is bound to ask to what extent the traditional techniques of persuasion are effective in the transformation of habit and opinion. The answer suggested by some recent research is not too reassuring. Kurt Lewin, the American psychologist, concluded after

1. J. E. Gordon, 'Plastics in Engineering', *Aircraft Production*, Jan. 1953, p. 3.

exhaustive experimental work on the changing of food habits that the mass approach by propaganda does not effectively bring about a change. In a survey for *Fortune Magazine,* of American business propaganda, W. A. Whyte[1] produces considerable evidence to show that mass communication can in some circumstances be both a blunt instrument and a two-edged sword. He quotes, for example, the view of a top American psychologist who worked on the United States Army's *Why We Fight* series of films and lectures, a tremendous effort to indoctrinate the American soldier. Their result was: 'Nothing . . . just about nothing'. The scientific report[2] on research to evaluate the success of these films is less categoric, but the conclusions point in the same general direction as far as the effect on general opinions and motivation is concerned. And they are supported by research into British miners' attitudes by the Acton Society Trust:[3] 'Before any information can be effectively absorbed, radical changes of attitude are necessary'.

This relative failure of mass information and publicity to produce changes of outlook and behaviour will no doubt be reassuring to those who resent the manipulative powers of propaganda. However, such comfort is offset, particularly for those who like to believe that the facts of science carry their own conviction, by the consistent result of investigations by American social psychologists into methods of changing behaviour: facts, no matter how eloquent of the need for change, do not produce results of themselves.

The investigations leading to the above finding[4] arose initially from a practical administrative problem with which the American Government was faced during the 1939-45 war: how to get people to change their food habits. Different methods, such as propaganda, lectures giving the facts of the situation, and group discussions were tried. Similar experiments on the introduction of new methods in factories have since been carried out.[5] Changes in food habits and in shop-floor practices in industry may seem to be far removed from the conversion of backward managements to a recognition of the value of science in industry. But they all have this in common: they involve changes in habit and outlook. These findings may have a special

1. The articles resulting from this survey are collected in W. H. Whyte, Jr. and the editors of *Fortune, Is Anybody Listening? (How and why U.S. business fumbles when it talks with human beings)*, Simon and Schuster, New York, 1952.
2. Carl I. Hovland, Arthur A. Lumsdaine and Fred D. Sheffield, *Experiments on Mass Communication, Studies in Social Psychology in World War II*, Vol. III, Princeton University Press, 1949, espec. p. 254-67.
3. *The Workers Point of View (Studies of Nationalized Industries, No. 11)*, Acton Society Trust, London, 1952, p. 13.
4. *The Problem of Changing Food Habits (Report of the Committee on Food Habits)*, National Academy of Sciences, Bulletin No. 108 of the National Research Council, Washington, October 1943; K. Lewin, 'Group Decision and Social Change', *in* Newcomb, Hartley, *et al., Readings in Social Psychology*, Henry Holt, New York, 1947, p. 330-44; M. Radke and D. Kislurich, 'Experiments in Changing Food Habits', *Journal of the American Dietetic Association, 23*, 1947, p. 403-09; *Manual for the Study of Food Habits*, National Academy of Sciences, Bulletin No. 111 of the National Research Council, Washington, Jan. 1945.
5. L. Coch and J. R. P. French, 'Overcoming Resistance to Change', *Human Relations, 1*, 1947-48, p. 515-31; A. J. Marrow and J. R. P. French, 'Changing a Stereotype in Industry', *Journal of Social Issues*, August 1945, p. 33-37; J. Levine and J. Butler, 'Lecture versus Group Decision in Changing Behaviour', *Journal of Applied Psychology, 36*, No. 1, p. 29-33.

importance for the scientist, for it is part of the ethics of the scientific world that salesmanship should be eschewed and facts allowed to speak for themselves.

This is neither a full nor adequate appraisal. What has been suggested is that there is a good deal of evidence to show that neither the straightforward presentation of facts nor the high-pressure techniques of modern publicity are likely to be very successful in transforming traditional attitudes and practices that block the widespread application of scientific and technical knowledge.

The Social Basis of Industrial Change

The results of the American research referred to above suggest several reasons for this apparent inadequacy of propaganda techniques. First of all, the process by which changes in traditional methods and ideas take place is a social rather than a personal one. In other words, it is less the result of due reflection and consideration on the part of the individual than of the pressure of group and public opinion. If this is the case, the implications for the methods of liaison work between research organizations and industry are fairly obvious. First and foremost, industries and other groups of science users cannot be approached as unorganized agglomerations of individual units; it is necessary for research organizations to have some knowledge of the social structure of the group of users they serve. Key organizations or individuals for particular innovations need to be located; since, if they are won over to the new methods suggested by research, they in their turn will influence whole groups of firms, and the social mechanism by which changes take place will thereby be started. In effect, this is the common phenomenon of fashion. Indeed, study of the rate of spread of innovations shows considerable evidence of a 'bandwaggon' effect, and this could be explained by the 'follow-my-leader' principle which is easy to observe in all fashion movements. There can be no doubt about the operation of the fashion principle in the field of management techniques such as time study, materials handling, joint consultation and 'communication'; and there is no real reason to assume that management decisions in the technological field take place in a way that is markedly different.

A further consequence of the social nature of the change process is that, as far as possible, innovations requiring changes in approach and practice should be introduced through existing opinion-forming groups in an industry. Every opportunity should be seized to make them the subject of public debate and informal discussion, and less reliance than is customary should be placed on written reports. In fact the launching of a report should be considered as the beginning and not the end of the effort to get the results of research applied.

Given this social basis of industrial change, the weakness of mass information and propaganda methods lies in the fact that they are blind in their approach to the target group; they cannot be steered to the points sensitive to change. Also, because they place the individual, to use the words of Lewin, in a 'quasi-private, psychologically isolated situation',[1] they fail to start off the process of social discussion that has an impact on the climate of opinion. The way to success, according to the results of these investigations by American social psychologists, is to involve the key groups of potential users in the discussion concerning the utilization of the research results, and to gain their participation in decisions concerning action to be taken. It is in this way, by a group decision, that the users become committed to and psychologically involved in the decision. Other things being equal, there is therefore much to be gained by associating the potential users of research with the early stages of a project.

The conclusion to which we appear to be drawn by the results of these experiments is that the most effective techniques of persuasion are those which, in result even if not by intention, are essentially democratic. Backward firms and industries are not to be won over to the use of new methods, and to the full exploitation of existing scientific and technical knowledge, by a flood of publicity and information. Only group discussion with potential users, involving them in decisions to apply the results of research, can produce the necessary change in outlook and behaviour.

This conclusion needs to be examined carefully, particularly since it supports the current gospel of 'democratic group participation' that is emerging from many studies by American social psychologists. One needs to ask, for example, whether the characteristics of group discussion methods that account for their success cannot be incorporated in the traditional techniques of publicity and propaganda. If participation is so vital, and if in consequence the critical weakness of mass communication techniques is that they are based on a one-way process of communication which prohibits such participation, can they be modified to take account of this? Such a question is especially important because, no matter how desirable, group discussion methods cannot easily be used where there is an undifferentiated and unorganized mass of users, for example householders or road-users. As an example of what might be done to combine participation and mass coverage, there is an interesting series of BBC television programmes on 'Science in the Making'; by asking viewers to complete and return questionnaires relevant to research being carried out at university and other centres, a real measure of audience participation is obtained. This would seem to be a much more effective way of changing the public attitude to scientific research than all the learned radio lectures.

1. Kurt Lewin, op. cit., p. 336.

As a further caution it must be repeated that the American research findings only apply where the effective digestion of research results by industry requires a changed outlook and approach to the problems of production. Many firms, especially the larger ones, and particularly those in the 'laboratory' industries such as chemicals and electrical engineering, will lap up anything of value put within their reach. Many innovations, especially the relatively minor ones following on a major technological change, slip in smoothly enough. In contrast, change of outlook is a pre-condition of the more effective utilization of scientific and technical information by the small-firm craft industries. Thus, there are different requirements for different situations, and the question arises whether the industrial liaison officers and services of research organizations should not concentrate on the breaking down of negative attitudes towards the use of science by direct contact with users—a job which conventional publicity techniques do relatively poorly—rather than conveying information to the converted—a job which they do so well.

DECISIONS TO INNOVATE

There is, however, one further limitation to the contribution these findings can make towards understanding situations created by technological change. Stripped to bare essentials, the thesis of the group of American social psychologists to whose researches we have referred is that the tactics and techniques of introducing a change have a critical influence on decisions to innovate or accept change. For the situations studied by them this is undoubtedly true. But it is important to note that, in their experiments, the habits changed were of the kind that are unconscious, irrational and rooted in traditional prejudices; whereas decisions to adopt or resist technical change in industry tend to be based on conscious self-interest. This distinction is not absolute, but it is nevertheless useful. Indeed, there are special reasons why conscious self-interest looms large in technological change. First, technological change concerns livelihood. Second, it is usually based on formal decisions, as against the more or less unconscious drift of other changes in behaviour. Third, it usually depends on voluntary acceptance; compulsion of management is in practice impossible. Thus, in contrast to many other kinds of change, technological change usually follows conscious decisions based on bargaining and negotiation between entrepreneurs and banks, and between employers and labour. Such decisions give the widest possible scope for the play of self-interest, as it is perceived by the interested parties. This appears to be borne out by a recent investigation by the British Institute of Management: 'healthy change grows out of need . . . when need is felt, then

is the time to adapt. When there is no need, or when the need is not recognized, any change has to be enforced and is usually resisted.'[1]

Economics and the Human Factor

Since self-interest is such a potent factor governing decisions to innovate, the impact of economic forces on the process of technological change is of obvious importance. We must know how the working of our economic institutions involves the participants in gains and losses. Simply stated, this boils down to the fact that our economic system is such that innovation must pay in the long run, and at the time of adoption managements must believe that it will pay; furthermore, workers and unions cannot be expected to welcome technological advances that affect their interests adversely.

It may be thought, however, that such economic forces operate as a mechanism built into the framework of our economic institutions, and that they have nothing to do with the human element, except insofar as it provides the medium through which they do their work. Indeed, many economists make precisely this assumption; 'market', 'money', 'demand' and 'capital' are studied without any reference to people who buy, sell, save and invest. There is clearly nothing wrong with this—as long as the abstractions lead to understanding and, finally, to ability to predict. Moreover, there are many problems in the field of technological change that require to be tackled by the traditional techniques of economic analysis. Examples are: the effect of competition and monopoly on the adoption of new products and processes; labour costs as an incentive to technical innovation; fiscal policies and their effect on the profitability of innovation. But when the framework of economic forces has been painted in, we would deceive ourselves if we thought that this provides an adequate theory for explaining the making of decisions in the technological field. For these are not made by automatons built on the model of 'economic man', but by businessmen who have ulcers and belong to social clubs. In the field of technological change, there does in fact seem to be a special need for research that covers not only the logic of economic institutions and forces, but also people's reaction to them in the rough-and-tumble of everyday life.

Let us take one or two examples of this. There is some evidence of a belief in industry that the first firm to develop a new process or product bears development costs not shared by the competitor who steps in at a later stage and is thereby enabled to put the final touches to a project that has fallen short of commercial success, or alternatively to produce a product commercially superior to that of the pioneer company. In the early history of alkali manufacturing, for example, there was a succession of firms that went

1. J. F. Scott and R. P. Lynton, *Three Studies in Management*, Routledge and Kegan Paul, London, 1952, p. 142.

bankrupt in the attempt to develop the process; the history of this is cited as 'some indication of the difficulties which confronted the early alkali manufacturers and indeed all development processes'.[1] In the electric lamp and aero-engine industries the big firms have usually remained aloof until commercial success was at hand. Clearly, if it is widely believed in industry that the wise man is second or third and not first in the field, the effect on decisions to innovate must be considerable. What one would like to know is how general this belief is, and for what sorts of innovations it is valid; in other words, to establish the extent to which industrial folklore on this subject conforms with economic fact.

The same sort of issue arises in connexion with the impact of technological change on the level and distribution of employment. Those desirous of removing all obstacles to increased productivity tend to hold the view that technological progress raises the level of employment and increases the standard of living; on the other hand, workers and trade unions see jobs threatened by new techniques and processes. To some extent, of course, these difficulties arise because the two sides think in terms of a different time scale: one side thinks of the 'general interest in the long run'; and the other, of the immediate loss of earnings and livelihood by a particular group of workers. At all events these are firmly-established social attitudes about the operation of economic forces, and as such they have an important effect on the introduction of new methods, and consequently on productivity. It is therefore of considerable importance that economic research should determine the precise ways in which technological change affects employment, so that labour's interest in protecting employment can be reconciled with that of management in improving the techniques of production. But all the economic research in the world will fail in its practical effect if no account is taken of the way in which the industrial folklore on this subject has been built up, and of what can be done to change it.

The Social System and Decisions to Innovate

The relationships between social values and organization, between political systems and developments in technology and science are so complex as to be a fruitful field for arguments of the 'hen and egg' type. However, since so much of the available literature on this subject centres on the impact of technology on society, rather than vice versa, perhaps this in itself provides sufficient excuse for turning the tables to consider how the structure and conventions of society affect decisions to introduce new products and processes. There can be no doubt that, from the point of view of those with a practical responsibility for promoting the introduction of new products,

1. Sir Frank Heath and A. L. Heatherington, *Industrial Research and Development in the United Kingdom*, Faber and Faber, London, 1946, p. 23.

processes and methods in industry, there are many social and human obstacles to technological progress. It may be true, of course, that the men of affairs are concerned with obstacles and difficulties which, though important in the short run, are overshadowed in the long run by the imprint on society of the giant strides of technology. But even if this is the case, there can be no doubt that these human and social obstacles to advances in technology do affect the prosperity of firms and, possibly, the destiny of industries.

In the United Kingdom, the awareness of this effect of social attitudes and values on the economic life of the country, and on the rate at which new ideas get adopted, has been enormously heightened by the reports of the 66 Anglo-American productivity teams that have crossed the Atlantic in order to discover the secret of American productivity. In his analysis of the experience of these productivity teams, Graham Hutton[1] pinpoints as an important factor certain characteristics of American society: 'Readiness to venture, to vary, to break with traditional practice, to innovate, to anticipate change in consumers' wants, or to create the change by correct anticipation of what the consumer can be induced to want—these are outstanding American characteristics'. Commenting in like manner on the British scene, Professor R. S. Edwards[2] has said: 'In our system of social values, as well as in our system of economic rewards and penalties, the determination to force through new developments, to take risks and assume the burdens that this implies, will have to regain some of the prestige that they have lost over the last half century'. And in a comparative study of French and American entrepreneurs, Sawyer[3] says of the French business psychology: 'Old customs, old products, old qualities, old methods have had a social sanction that specialization and mass production have never had', and later: 'French entrepreneurship has repeatedly failed to exploit the very great scientific and technological innovations that France has produced'.

Attitudes towards change in industry are psychologically linked with more particular aspects of behaviour of the business world, for example the secrecy of methods and practices. The reluctance of many European manufacturers to exchange information, to take a chance on gaining more than they lose by a mutual picking of brains, is a factor of undoubted importance so far as technological change is concerned. For only by such an open exchange of practice and viewpoint can a high average level of industrial efficiency be attained, and the gap between the most efficient and the least efficient firms to some extent be closed. There can indeed be no doubt that there are fundamental social differences from country to country in attitudes to change,

1. Graham Hutton, *We too can prosper*, Allen and Unwin, London, 1953, p. 129.
2. R. S. Edwards, 'The Future of Industrial Research', *Research*, June 1952, p. 247-55.
3. J. E. Sawyer, 'The Entrepreneur and the Social Order', *in* W. Miller, *Men in Business*, Harvard University Press, Cambridge, 1952, p. 18 and 19.

and that these attitudes are linked intimately with a whole range of satellite conventions, customs and beliefs that affect the businessman in his everyday decisions.

Furthermore, social values far removed from the economic and technological spheres may act as brakes on innovation. The development of the typewriter was slowed down because it became involved in the political and social aspirations of the young ladies who proposed to use it.[1] Another important technological innovation, the bicycle, also became involved in the battle for women's emancipation as well as the target for religious and medical opposition; several maladies specific to bicycle-users, for example 'kyphosis bicyclistarum' and 'bicycle face' were discovered and recruited to the armoury of the militant opposition.[2]

Finally, there are groups in society, apart from the businessmen, whose strategic position in the realm of technological change gives them special importance. Bankers and scientists are the obvious examples. Such groups have their own special social structure and customs that impinge on technological progress. The fact that the Brahmins of the scientific world, at least in the United Kingdom, are the pure scientists and that applied scientists have comparatively low status and prestige, undoubtedly has something to do with the gap that exists between the discovery of new knowledge and its application in industry. Of like importance are the customs and conventions of the world of banking with regard to financing technological development.

It would not be difficult to multiply examples of how the pace and direction of technological innovation are affected by social attitudes. But there is another way, perhaps more important, in which society intervenes: the sources from which the leaders of industry are recruited determine to a significant degree the outlook towards new methods and techniques, and these sources are of social rather than economic determination. Outstanding examples of this are seen in the craft industries based on the small family firm, where the continuity of traditional practice is assured by the heritage of son from father. Here the emphasis is on nurturing a modest family fortune, an emphasis vastly different from that of the professional manager who goes to the capital market, of the entrepreneur who sinks his own fortune and that of his close friends in a risky venture, or of the boards of nationalized industries who are obliged to weigh up where the public interest lies. It is obvious that the extent of enterprise and innovation will depend largely on the proportions of these various types of leaders which make up the industrial elite in any country, and on the extent to which new blood, and therefore new ideas, can get to the top. In particular it is important that new sorts of industrial leadership should emerge as the character of industry changes. In Schumpeter's

1. Bernhard J. Stern, 'Resistance to the Adoption of Technological Innovations', *in Technological Trends and National Policy*, U.S. National Resources Committee, p. 49.
2. Sydney H. Aronson, 'The Sociology of the Bicycle', *Social Forces, 30*, March 1952, p. 306-07.

terms, innovation depends on keeping the way to top management open for the 'strong wills and strong intellects'. It is interesting to ask in this connexion whether scientists, despite growing pressure for their greater participation in managerial decisions, are the people best suited by training and outlook to see the economic opportunities opened up by scientific and technological innovation. In his book on the radio industry, Maclaurin[1] draws attention to certain basic facts concerning the role of management in translating fundamental discoveries into commercial products: 'the most successful companies have been dominated by strong personalities who were *innovators*. This applies to the Marconi companies, R.C.A., Philco, Zenith, Emerson and Sylvania . . . *none* of them was dominated by an inventor. . . . The executives of these companies showed the same intensity of purpose as the pioneer inventors, but their interests and instincts were in commerce rather than in science'. The needs of industry have changed, and a new type of scientist-manager has emerged, but the picture painted by Maclaurin is sufficiently categoric to make one ponder the question of recruiting scientists to management boards.

Organizational Conservatism

If the general social attitudes and structure of a society have an important influence on decisions to innovate, so too has the hard and resistant crust of custom that develops in individual organizations. One of the most regular and striking features of important innovations, as opposed to minor improvements in known techniques, is the frequency with which they are developed by organizations without an established position in the field. Fessenden, one of Marconi's American competitors, is reported by Gilfillan[2] to have gone so far as to say: 'No organization engaged in any specific field of work ever invents any important development in that field; or adopts any until forced to by outside competition'. This is undoubtedly an extreme statement of the position, but there is abundant evidence to show that it puts the finger on a most important fact. Maclaurin shows that in 1900, despite the prediction of the British scientist Crookes, the principal organizations in the field of electrical communications were oblivious to the commercial possibilities of wireless telegraphy. Bright[3] remarks that, in the electric lamp industry, independent scientists and inventors did the pioneering work, whereas the leading European and American lamp manufacturers adopted the new ideas at a relatively late stage. The same applies to the development of turbo-jet engines in Great Britain and Germany, and the liquid-cooled

1. W. Rupert Maclaurin, *Invention and Innovation in the Radio Industry*, Macmillan, New York, 1949, especially p. 249 and 21-23.
2. S. C. Gilfillan, *The Sociology of Invention*, Follett, Chicago, 1935, p. 91.
3. Arthur A. Bright, *The Electric Lamp Industry*, Macmillan, New York, 1949, p. 449 and 456-7.

engine in America; in all these cases the pioneering work was done by small firms and not by the successful producers of aircraft engines.[1]

There is, of course, a degree of economic logic in all this. Having gained production momentum, an industrial organization is in a difficult position to know at what stage it becomes profitable to transfer energy and resources to new projects. So the sluggishness of established firms to respond to new technological opportunities may spring not so much from blissful ignorance of commercial possibilities as from the desire to defend their economic interests. Nevertheless, sheer conservatism, inability to grasp the significance of new ideas, or failure to get a large-scale organization out of the grooves in which it is running, are also important reasons for the 'outsider' phenomenon in technological change.

What are the characteristics of organization that explain this? There is first of all the simple fact that in large-scale centralized organizations the number of effective decision-takers is remarkably small, as is even the number of those who effectively have the ear of top management. In consequence it is not infrequent to find, within a large concern falling into stagnation, a minority with the ideas and energy necessary for salvation but without the means of communicating to the top and therefore of getting the organization to change direction. Stagnation may thus partly arise because the points at which the spark of a new idea can be kindled are fewer, and partly because ideas within the organization never get communicated to the decision-takers. There is in addition the natural tendency for any organization to develop its own customs, ritual forms of action and myths; over the course of time these become effective barriers to action.

Paradoxically enough, such barriers are frequently strongest in organizations dominated by an outstanding innovator. For the creative gospel of one period becomes the dogma and ritual of the next, and the advocate of change turns into a defender of the *status quo*. The process by which this happens is quite characteristic. The innovator becomes psychologically identified with the new practices and methods for whose introduction he was responsible, and resists their being eclipsed by newer ways more adapted to the changed needs of the organization. Even when absent or dead, he remains a powerful force in the battle against innovation; for his lieutenants use his memory as a bulwark against change.

To some extent the case of the organization dominated by a powerful personality is an extreme one, but there is something of it in the history of many organizations. Moreover, it throws up a more general issue of crucial importance as far as technological change is concerned: how to maintain creative leadership within the very big organizations that are now so largely

1. Robert Schlaifer and S. D. Heron, *Development of Aircraft Engines and Aviation Fuels*, Harvard Graduate School of Business Administration, Boston, 1950, p. 13 and p. 86-7.

responsible for technological progress. This is a complex matter. For as we have stated above, there is a natural tendency for those at the apex of an organization to become, over a period, psychologically identified with procedures, policies and objectives that they have pioneered. It is in fact difficult for most people, even over comparatively short periods, to maintain a fresh and self-critical outlook. This is borne out by the spate of change that usually follows a change of leadership, only to be succeeded by a new but equally rigid *status quo*. It would certainly be rash to suggest that there is a fixed period after which the blinkers grow and the grooves of action and attitude become well developed, but for most people five years is probably not very wide of the mark. If this is the case, then one might conclude that a high rate of managerial mobility is necessary if organizational stagnation is to be avoided. Illustrative of this is Passer's[1] conclusion about the attempts of the American inventor F. J. Sprague to introduce electric elevators and multiple-unit control on electric railways: 'Sprague's experiences seem to indicate that major innovations first appear where there is a new firm or a new management which because it is new does not feel committed to traditional patterns of business behaviour'. Furthermore, the high rate of circulation of top executives which is characteristic of American business may explain the speed with which new ideas spread in that country.

At all events, organizational conservatism has a real influence on decisions to innovate. For the businessman is influenced in his economic decisions not only by social values, and by his own social origins, but also by the immovability or flexibility of the organization he leads, its inertia or ability to strike out in new directions, and most of all the extent of his own immersion in the customary way of seeing things.

THE IMPACT OF INNOVATION WITHIN THE FACTORY

Once the decision to innovate has been taken, the final link in the chain between the laboratory and the market has to be forged: installing the new process or developing the new product within the factory. This is a stage in the application of science and technology for which the scientist has no direct responsibility. But since it manifestly affects the extent to which economic results flow from his work, he is bound to take an interest in it. And for the industrialist, it is this final stage that is the most important, for without the successful translation of a potentially profitable scientific invention into a marketable product and a smooth production plan, a decision to introduce technological change can only lead to a great loss of money and energy. Furthermore, it is at this final stage that the impact of technological change

1. H. C. Passer, 'Frank Julian Sprague', *in* W. Miller, op. cit., p. 236.

on existing habits and behaviour, both of management and operatives, is strongest; it is here that the human factor becomes of supreme importance.

The study of the impact of science and technology on society has tended to concentrate on the broad social effects: for example leisure, the family, art and literature, the tactics and strategy of war. But there is a growing body of evidence indicating that the short-run effects on the factory as a social organization, as a small society in its own right, are of very considerable importance. First of all, this is because it is in the factory, perhaps more than elsewhere, that new technology affects social activity and the quality of the individual's participation in it. For example, developments in production technology, such as the mass-production assembly line, affect both the individual's satisfaction with his immediate job, and the social meaning it has for him. The second reason for the importance of the short-run effects within the factory is that such effects can result in resistance to changes, inefficient operation of new techniques or processes, delays and frictions during development, or even the complete blockage and shelving of innovation projects. Scoville's study, for example, shows how the technical revolution in glassmaking had to await the development of techniques that could be operated without the existing skilled workers.[1] There are, of course, many other examples of Luddite attitudes on the part of the workers and their unions. But whilst the effect of technological change on the kinds of skills and number of workers required is of extreme importance, there has been a tendency to think of the problem of resistance to change exclusively in these terms. It is more fruitful, however, to consider technological change as something which, within an individual concern, requires a considerable adaptation of attitudes, of work organization and of accepted practices; as something which in effect disrupts the existing social organization of the factory. Its impact may be felt in any or all of a variety of spheres: the balance of power between the various functional groups in management may be displaced; the relative status and prestige of jobs may be changed; existing work teams and sections may be broken up; established ideas and assumptions about production may have to be replaced by newer ones; the scope and nature of promotion opportunities may be altered; and so on.

These ideas are best developed by reference to actual cases, two of which are given below. The first of these is taken from a study carried out by Ronken and Lawrence[2] at the School of Business Administration of Harvard University; it concerns the development of a new product by a firm in the electronics industry. The second is a discussion of the way in which the systematic introduction of automatic control techniques, as a major potential

1. For a discussion of this, see Yale Bozen, 'Studies in Technological Change', *The Southern Economic Journal*, April 1951, p. 441.
2. Harriet O. Ronken and Paul R. Lawrence, *Administering Change—A Case Study of Human Relations in a Factory*, Harvard Graduate School of Business Administration, Boston, 1952.

trend in production technology, may affect the factory as a social organization.

The Case of the 'Amicon Tube'

The 'Amicon Tube' is a pseudonym for an electronics device pioneered and produced by a medium-sized American electrical engineering firm. The purpose of the study in question was to follow through, mainly by observation on the spot over a period of many months, the vicissitudes of the product's development from the original idea to the successfully-marketed product.

The development of this new product was viewed by the top management in the firm in question as a matter of urgency, because commercial advantage in their industry—and this applies to an increasingly wide range of industrial activity—depended on rapid, 'hot-house' transformation of novel scientific and engineering ideas into marketable products. Despite this pressure to develop and market the new product, the project ran into trouble all along the line. But the causes of delay were due not so much to technical difficulties as to those of personal relationships. The researchers concluded that 'these problems of relationship were the most critical factor in determining the results of the project'.

Co-operation between the different functional groups within the factory appears to have been the core of this 'problem of relationship'. In fact, it is characteristic of this type of work that a high degree of co-operation is demanded from groups concerned with pushing through from the novel scientific or technical idea to routine production of a saleable article. There were three functional departments concerned in this factory: development engineering, industrial engineering and production. Between them they were responsible for the whole span of product development: the development engineering department for design and experimental work; the industrial engineering department for production methods, processes and standards; the production department for routine production of products for the market.

The 'Amicon Tube', it so happened, was the brain-child of the industrial engineers, and not that of the development engineers. In order to get into production as soon as possible, the management gave the industrial engineers clearance to go ahead with the project, regardless of the fact that this led to trespass on the preserves of the development engineers. A change in the established relationship of the two functional groups was thereby introduced, ultimately leading to a conflict between them. The final result was that the two departments were working on precisely the same technical problems raised by the development of the new product, without any exchange of ideas or results between them. Indeed, there is a distinct suggestion that the experiments in the design engineering department were carried out as a

means of 'monitoring' the industrial engineers, and the results were used to 'shoot them down' just as much as to contribute towards the development of the product.

Similar difficulties were met in passing from the experimental stage to routine production. The pressure to get commercial results led to the transfer of control, at a stage when some development problems still remained to be solved, from the industrial engineers to the production department. The industrial engineers responsible for the experimental stage resented losing the project to production, and uneasy relationships developed between them and the production foreman. The hand-over was further complicated by the fact that the operatives on the experimental work had identified themselves with the engineers, and felt a loss of status and prestige on being transferred from the glamour of experimentation to the routine of production. The net result was the development of friction and lack of communication between the industrial engineering and production sides, one symptom of which was complaint from production that the programme was falling behind schedule because the necessary equipment was not forthcoming from the industrial engineers.

In terms of results, the project got into serious difficulties as a consequence of the lack of collaboration between functional departments. Typical of the situation at this stage was the tendency to seize on evidence in order to prove that the project was 'good' or 'bad', rather than to use available effort and knowledge to achieve the company's objective. Six months after the product had officially been put into production not a single article had reached the market. In the end, this led the top management to put the product back to the development stage, this time under the exclusive control and supervision of the development engineers.

This may be a fairly typical story of product development. Its importance lies, however, in the demonstration that new products based on research and development may be seriously delayed because of a failure to realize that technological change involves people, their interpersonal relationships, their relative status and power, as well as new combinations of materials and processes. And this lesson may be particularly worth learning in view of the increasing importance of *rapid* product development in many industries, especially the science-based industries where the frontiers between research, product development and production are becoming increasingly blurred, with a consequently growing demand for collaboration between the various functional groups.

The Possible Impact of Automatic Control

Our second example is of much wider significance and scope; it concerns one of the major developments in production technology. It is only too easy

to over-dramatize the possible effect of introducing automatic control principles and techniques in industry, but there is no doubt that their impact is bound to be considerable. Meier is quoted by Diebold[1] as having listed the industries in America that he believes to be ripe for 'automation' as follows: bakery products, beverages, confectionery, rayon, knit goods, paperboard containers, printing, chemicals, petroleum refining, glass products, cement, agricultural machinery, miscellaneous machinery, communications, limited price retailing (i.e. mass retailing of standard items) and some miscellaneous items. These account for 8 per cent of the present total labour force. Other industries totalling some 56 per cent of the labour force are likely to be affected marginally.

Even if the prophecies about the advent of the completely automatic factory prove to be exaggerated, there can be little doubt that marked advances in the extent and nature of mechanization are under way. The impact on economy and society at large may or may not be as dramatic as is predicted, but the practical problems of factory organization raised by these changes are bound to be considerable. Dislocation of the factory as a social entity may lead to obstacles and resistance, and the nature of the potential disturbance needs to be examined if the possible difficulties are to be met.

In the first place, the introduction of automatic control will depend on changes in traditional ideas and customs about the nature of the production process. Thus Diebold[2] has stressed the need for new thinking about process, product and machine design, and particularly about the relations between them; products will need to be redesigned in terms of the automatic control process, rather than applying the more usual procedure of designing the process in terms of the product. As another example, the mechanization of office operations, which is a fruitful field for the application of automatic control, may meet with resistance from office workers because it is a threat to the superior status of brain work as opposed to manual work.

Changes in the constitution and structure of the labour force are obviously also involved. As the introduction of automatic control becomes more feasible from both the economic and technical standpoints, the proportion of machine minders monitoring automatic control devices, as compared with operatives on repetitive manual work, is bound to increase. There is also likely to be an increasing predominance of specialist engineers with the skills to keep the production line moving. These changes in the constitution of the labour force will bring with them all the usual personnel problems associated with the introduction of new methods and processes: re-training, re-allocation of the labour force, redundancy. Furthermore, the horizontal split in technical

1. John Diebold, 'Automation—The New Technology', *Harvard Business Review*, November-December 1953, p. 63-71.
2. Op. cit., p. 66-7.

training and status between university-trained engineers and machine minders with relatively little training may have a profound effect on promotion possibilities for the rank and file. For the gulf between them may be too wide to bridge by the acquisition of knowledge and experience within the factory.

The structure of factory work teams and the nature of human relations within and between them are also likely to be modified. The important effect of these features of work organization on morale and efficiency in factories with mass-production assembly lines is only now being recognized. If automatic control is systematically applied, the pattern of human relations typical of these contemporary assembly lines will be transformed, and instead of adjacent groups of operators on related manual tasks of a repetitive kind, there will be a thin spread of machine minders on an extensive floor-space. Clearly, the basis of job satisfaction, as it is affected by relations with other workers and the immediate nature of the job, is bound to be quite different.

Management organization and structure is also likely to be affected. The essential working link on the production line under automatic control is between the machine minder and the specialist engineer, so that as faults develop they can be rapidly put right. Delays become very costly indeed, so that the overriding need for establishing an effective working contact between machine minder and specialist engineer may lead to the elimination or by-passing of the intervening line foreman. Such a development will lead to a decline in the importance of the production function as compared with specialist functions such as servicing, maintenance and control, and to a general outmoding of the concept of 'line' management.[1] Relative status and power of specialist departments are also likely to change. The growing importance of product design, for example, arising from the need to design product in terms of process rather than vice versa, is likely to lead to quite different relationships between development (or design) engineers and production engineers. Furthermore, time and motion study of manual operations is likely to diminish in importance relative to techniques such as process control, plant layout, handling of materials, etc. Maintenance as a function will increase in importance.

If there is a lesson to be learned from the story of the 'Amicon Tube', then it is one that can be applied with profit to the problems of introducing automatic control techniques in industry. For the ease and efficiency with which such techniques can be extensively introduced will to some extent depend on whether the human problems, such as changes in the relative status and power of different functional groups in management, are anticipated and dealt with accordingly.

1. 'The Factory of the Future' (Part I), *Factory Management and Maintenance*, Vol. 110, No. 4, April 1952, p. 101-02.

CONCLUSION

It is clear that the ease and rapidity with which the economic fruits of new scientific and engineering ideas can be reaped may depend to a considerable extent on human obstacles and difficulties. This deserves to be said if only because there has been a tendency to think of science and technology as affecting, but not being affected by, society. But the difficulty about the present position is that, whereas we know a good deal about the range of factors—human, financial and technical—that affect the rate of application, we know virtually nothing about their relative importance. This is a vital gap in knowledge for those concerned with practice rather than theory. For the scientific administrator and the industrialist are not so much concerned to know which of the factors *might* intervene, as to know which of them contributes the *critical obstacle* in a given situation. The answer will obviously be different for the various sectors of industry, and for the various scientific and technical fields. From the practical point of view, therefore, the need is not so much for research in terms of the concepts and theories of individual academic disciplines, but for operational research geared to the problems of those with responsibility for getting science and technology applied.

The need for such a critical examination of these problems of research application is becoming more pressing for a number of reasons. For one thing, firms in many branches of industry need to suck in and exploit a tremendous—and increasing—amount of technical and scientific information if they are to survive. As the rate of technological change increases and the impact of science on production becomes more direct and immediate, the problems of human adaptation emerge with greater clarity and precision. But most important of all, perhaps, is the fact that, with the growing burden on the public purse, the pressure for economic results from scientific research is growing. If science must pay to get public support, then the scientist must descend from his ivory tower and seek to remove whatever obstacles prevent his work from having the maximum economic impact.

In the past, the role of the human element in all this could perhaps be ignored by the scientist. For insofar as the human factor was thought to be of any significance, it was conceived of in terms of labour resistance to new technology—and therefore something which concerned the industrialist rather than the scientist. But the picture is changing. For there is growing evidence that the human element intervenes most decisively at the stage of management decisions to innovate. Such decisions are influenced by, and therefore within the range of, the scientist's own operations. His responsibility is therefore engaged.

PHOTOSYNTHESIS AND ALGAL CULTURE

by

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A great deal of experimental work has been directed to the better and more direct utilization of solar energy. In the Pyrenees large concave mirrors are being used to produce very high localized temperatures for metallurgical processes; in the U.S.A. houses have been heated by the sun's rays, the heat being stored overnight by means of chemicals in tanks; and fresh water has been produced from sea water by solar distillation. These interesting investigations and many others like them have as yet made little quantitative impression on the problem, and photosynthesis, for which process man can take no credit at all, remains the only continuing major use made on earth of the sun's energy. It is perhaps somewhat impertinent in the circumstances to point out that it is not a very efficient process, particularly since man depends on it for all his food, whether animal or vegetable.

Laboratory experiments on the efficiency of light utilization in photosynthesis have led to widely varying results, depending partly on the conditions of experiment. Recently, however, it has been shown that in light of low intensity—and this is important—the efficiency may be as high as 20 per cent of the incident energy in the visible part of the spectrum. In full sunlight, however, the efficiency falls as low as 2 per cent or less, this probably being a fairly general average. This comparison provides a rough indication of the improvement in food yields which might be obtained if a more efficient use of the incident energy were possible.

CROP PLANTS

This 2 per cent of the proportion of sunlight falling on usable vegetation is, then, the fraction on which all mankind depends for its food supply in the form of normal agricultural crops of which the relatively small proportion usable is either consumed direct or fed to stock animals which are in turn eaten. Recurrent food shortages, sharpened by two world wars, have focused the attention even of the relatively well-fed western world on food supply, and the long-term disequilibrium between the rapidly increasing world

population and the much more slowly increasing rate of food production has been a subject of discussion ever since the classically pessimistic analysis of Malthus. The main shortage, both in the short and long terms, is protein. It is of interest to consider the yields of conventional agriculture as a convenient reference point, and some figures of typical crops as well as of maximum yields of tropical crops are given in Table I. For the most part, these figures give only a rough idea of the orders of magnitude involved.

TABLE I. CROP YIELDS (in tons per acre per annum).

	Total yield	*Dry matter*	*Parts normally used only*		
			Protein	*Carbohydrate*	*Fat*
Wheat (U.K.)	2	0.9	0.12	0.69	—
Potatoes (U.K.)	8	2	0.16	1.6	—
Sugar beet (U.K.)	11.2	2.5	0.1	2.6	—
Beans (U.K.)	0.86	0.75	0.2	0.43	—
Grass (U.K.)	—	—	0.27	—	—
Grass (U.K. max. figure)	—	—	0.6	—	—
Elephant grass (Hawaii, as forage crop)	70	14	1.26	6.6	—
Soya beans (U.S.A.)	1[1]	—	0.4	—	0.2
Oil palm (West Africa max. figure)	—	—	—	—	1.25
Tapioca (Java max.)	27	—	—	6.75	—
Sugar cane (Hawaii max. figure)	—	—	—	15	—

1. Approximately.

Such yields have, of course, been obtained by painstaking improvements in technique—including increasing applications of fertilizers—spread over very many years and involving no spectacular changes in magnitude. Moreover, when these yields are translated into animal protein—for which most of the human race has such a marked preference—the fall is striking. Animals are inefficient converters. Thus, the 600 lb of grass protein per acre mentioned in Table I, if fed to stock, yields about 54 lb of meat protein (390 lb of beef).

INCREASING OUR FOOD SUPPLY

The problems of getting more food to the acre other than by steady improvements in ordinary farming have been tackled in various ways. There is in young spring grass far more protein than the cow can convert, however inefficiently, into meat. Since grass is a high protein yielder, attempts have been made[1, 2] to extract the protein directly and use it as human food,

1. R. E. Slade, D. J. Branscombe and J. C. McGowan, 'Protein extraction', *Chemistry and Industry*, 23 June 1945.
2. N. W. Pirie, 'Leaf Protein', *Food Manufacture*, November 1947.

leaving behind probably enough for animal fodder. Difficulties encountered have included the non-existence of efficient machinery for the extraction and preparation of the protein; the probable necessity of operating in small units and the concomitant cost of labour and petrol for collection; and the uncertainty of how best to use the result. The first problem is being tackled; the second is an economic problem and it might be pointed out that if the cow is eliminated, a tractor and fuel have to be used instead, whereas the cow, however inefficient as a converter, does at least collect its own raw material; and on the third, rumour has it that grass protein has been fed to the unsuspecting High Table of a Cambridge College as green pea soup. Flippancy apart, the idea is basically interesting and work continues. The technical problems will no doubt be solved, but the economic outlook is less certain.

An alternative approach derives from the fact that the corresponding food chain—that is, the sequence from the green plant through the animal that eats the plant to the human being who eats the animal—exists in both salt and fresh water as well as on land. Experiments have been carried out[1] in fertilizing a sea loch (a procedure which may be regarded as analogous to fertilizing a land crop) with a resultant increase in the catches of fish, and fertilized tropical fresh water fish ponds are capable of giving such staggering yields—4,000 lb of fish per acre per annum has been quoted for ponds in South China[2] against the 400 lb of meat from an acre of meadowland—that efforts are being made to extend this form of fish farming to other tropical areas.

The organisms which form the lower end of the food chain in fresh and salt waters include, among many types, protozoa, diatoms and algae. The deliberate cultivation of algae under more or less controlled conditions to get high yields can be regarded as an attempt to short-circuit the aquatic food chain analogous to the protein-from-grass attempts on the land food chain. This is not, of course, the only attempt that has been made to grow micro-organisms as food. Yeasts, for example, have a very high rate of reproduction and are capable of producing great quantities of protein in a short time; they require, however, a fully-developed chemical plant for their production. Such a plant was erected in the West Indies, but does not seem to have been very successful. Much more recently some work has been reported on the culture of bacteria (*B. coli*) as a feeding stuff; this is the first time such a use has been suggested for bacteria. The major difference between such non-photosynthetic organisms as these and the photosynthetic algae is that the former must be provided with a chemical source of energy, usually

1. 'Fertilization of Sea Lochs', *J. Marine Biol. Assoc.*, Vol. 28, No. 1, 1949.
2. C. F. Hickling, 'Fish Farming in the Middle and Far East', *Nature*, 15 May 1948; and J. M. Brown and V. D. van Someren, 'New Fish Culture Methods for Tilapia in East Africa', *Nature*, 22 August 1953.

a carbohydrate (e.g. sugar) which may be relatively expensive, whereas the latter use the sun's energy and need only be provided with water, inorganic salts and carbon dioxide.

THE CHARACTERISTICS OF ALGAE

The algae are a multifarious group; the types familiar to most people include the macroscopic red, green, and brown sea-weeds. Apart from these, five main groups (*Chlorophyta, Euglenophyta, Chrysophyta, Pyrrophyta, Cyanophyta*) are mainly microscopic and are often unicellular. The unicellular varieties can exist in more or less uniform suspensions (which is of key importance for their cultivation on a large scale) and algae of this kind are responsible for the green discoloration of stagnant water. A picturesque example illustrates the size of these organisms: a quart of a moderately dilute suspension of *Chlorella*—the organism on which most work has been done—contains about ten times as many cells as there are people in the world.

We should consider briefly those characteristics relevant to intensive cultivation which differentiate algae from the higher plants. The higher plant must devote much of its material to providing a more or less rigid skeleton, and in consequence only a small part of the total weight of the plant produces a usable food material (this can be seen in Table I); the plant dies down in winter and therefore uses the incident sunlight during only a part of the year; the use of nutrients can never be completely efficient because of the impossibility of completely controlling the media involved, soil and air; in particular, the rate of supply of carbon dioxide, which may control the rate of photosynthesis, cannot be increased, although hydroponics goes at least some way towards this end in its substitution of culture solutions for soil. In contrast to all this, the unicellular alga, being supported in water, has no skeleton other than its cell wall and can thus devote a greater proportion of its material to useful ends (50 per cent of the dry weight as protein is common and up to 70 per cent has been reported); since all nutrients are supplied in solution, the medium can be completely controlled, waste virtually eliminated and growth rates kept at a maximum; and since such control is feasible, year-round growth is possible with resultant maximum utilization of equipment. It will be noted that absolute efficiency of utilization of sunlight has not been mentioned in this comparison; it was formerly thought that algae could use a greater proportion of the incident sunlight than could higher plants, but the latest information indicates that in practice utilization is probably about equally efficient in both types of organism. It should also be noted that algal culture, since it would require a special apparatus of some kind in any case, could be carried out on infertile areas of the earth. Evidently the unicellular algae warrant further investigation.

The subject has already received a certain amount of publicity but, in the complete absence of any published cost data, this has concentrated, understandably enough, on the attractive technical possibilities arising from the characteristics of algae as contrasted with those of higher plants, and the theoretical advantages of algae. The result of this rather one-sided approach has been to convey an optimism which is perhaps not wholly justified by the available facts. An attempt is made here to take a more comprehensive view and to assess the practical possibilities of algae, even though, in the present state of development, many of the considerations can be given as indications only.

LARGE-SCALE CULTURE[1]

The alga *Chlorella,* of which there are many different strains and species, is small (5-10 microns in diameter), round, and simple in structure; it has a chloroplast, a single nucleus and a cell wall which is commonly supposed to be cellulosic. One of the few good illustrations of the organism will be found in *Penguin New Biology*.[2] A cell from a young culture will be small and solid, with dense protoplasm; an older cell may be larger and vacuolated, that is, the protoplasm, instead of appearing solid, may contain clear spaces full of liquid cell sap. Reproduction is by simple cell division, and under suitable conditions cells will continue to divide at regular intervals, the interval between one division and the next being known as the generation time. Under the most favourable circumstances, the mean generation time of *Chlorella* is about 15 hours, so that accumulation of new material is very rapid. This, of course, is part of the attraction of algal culture, though it should be noted that this rate of growth is considerably lower than that of some other organisms; for example, it is less than half that of the yeasts and bacteria already mentioned.[3]

In a normal static culture freshly inoculated with *Chlorella* there will be an initial 'lag-phase' of growth while the culture adjusts itself to the new conditions, followed by an 'exponential phase' when the rate of increase in the total number of cells is at a maximum. Sooner or later—say in about fifteen days—the rate of cell division slows down, whether from shortage of nutrients or other causes, and the individual cells tend to grow larger, become vacuolated and acquire thicker cell walls. A growth cycle of this general pattern is common to most micro-organisms. During the exponential phase the protoplasm of *Chlorella* is dense and the protein content high;

1. John S. Burlew (editor), *Algal Culture from Laboratory to Pilot Plant*, Carnegie Institution of Washington, Publ. 600, Washington, D.C., 1953. This is the most comprehensive publication on algal culture.
2. G. E. Fogg, 'Chlorella', *Penguin New Biology*, No. 15, October 1953.
3. G. E. Fogg, *The Metabolism of Algae*, Methuen Sc. Monographs, London 1953.

during the later, stationary phase, the proportion of protein diminishes and fat tends to accumulate. It was demonstrated by Spoehr and Milner in work published in the U.S.A. in 1949 that these proportions could be controlled by variations in the growth medium. Thus high light intensity and high nitrogen nutrition in the exponential phase favour the accumulation of protein, whereas nitrogen deficiency in the stationary phase favours the accumulation of fat. Protein contents of 60 per cent and more have been reported, 50 per cent being common, and fat contents of 80 per cent and more have been achieved. This degree of flexibility is something which cannot be attained with higher plants.

Though algae such as *Chlorella* have been known to botanists for many years, the first attempts to cultivate these or related organisms on a large scale for practical purposes were made in Germany about 1941 when their ability to accumulate fat, which was then very short in Germany, was investigated. Practically all the subsequent work, however, has aimed at the production of protein, partly no doubt because the fat shortage was more easily remedied than the protein shortage, and partly because the accumulation of fat seems likely to be slower and economically less attractive.

The basic requirements for the large-scale cultivation of algae can be fairly simply stated. They must be fully supplied with nutrient salts, which include not only the major nutrients, such as nitrates and phosphates, but also elements such as iron and cobalt, known as micronutrients, which recent research has demonstrated to be essential, though only in minute quantities. They must be enabled to receive all the light they can utilize; and, to get the highest possible growth-rates and yield of protein, the culture must be kept in the exponential growth phase. This means that the daughter-cells arising from a cell division must be quickly removed from each others' vicinity so that each is immediately surrounded with a fresh supply of nutrients and enabled to continue growing at the maximum rate. The culture must therefore be agitated continuously. Some agitation would in any case be necessary in order to prevent the cells actually sinking slowly under their own weight and forming a layer on the bottom. In addition, advantage must be taken of the unique opportunity offered by a submerged culture for increasing the supply of carbon dioxide in the water, a step known to increase growth yields provided the carbon dioxide concentration is kept below the level at which toxic effects may appear.

It will be noted that the aim is to achieve a *continuous* growth of algae; the culture is maintained as far as possible permanently under optimum growth conditions, a proportion of it is regularly or continuously removed and the cells harvested, and the growth medium is 'topped up' with fresh nutrients and returned to the culture. Only thus will the economic ideal be achieved of maximum efficiency in growth rates, protein yield, and utilization of nutrients, ground area and equipment, though this may raise

further problems. Thus certain laboratory work some ten years ago seemed to indicate that if *Chlorella* was grown continuously in the same medium, a toxic effect developed which retarded further growth. This would hardly be surprising, since the slow accumulation of by-products of the growth processes might well have such an effect and the actual production of an antibiotic is a possibility which cannot be excluded; fortunately, this is one difficulty which has not yet been encountered in practice.

Further consideration immediately reveals that the above requirements may not be so easily met as it might seem at first and that some of them are conflicting. For example, to get the most efficient use of the equipment, particularly the harvesting equipment, one should obviously aim at obtaining the thickest possible suspension of algae; this, however, immediately raises practical difficulties in getting a supply of nutrients to the cells so that each is growing under the best possible conditions. This would apply particularly to micronutrients, the supply of which might, under the artificial conditions envisaged, need special attention in any case. Again, the greatest possible depth of medium should be aimed at in order to get the highest possible return per unit area of illuminated surface or per unit area of total plant, but beyond a certain point—which in practice so far seems to be a very few inches only—cells deep in the medium cease to get adequate illumination. Above all there is the problem of keeping the cost of the whole operation to a minimum in the hope that the product will be competitive under normal economic conditions. One way of satisfying all these conditions except the last would be to grow the algae in vertical tubes, thus at the same time getting the highest possible yield per acre and making the best possible use of the incident light. However, the high cost of such plants would make the idea quite impracticable.

The culture grown, the algal cells must be separated from the medium (harvested), dried out and stored. The drying is important since algal cells, if kept wet and packed together, would develop bad flavours and odours. However, these problems are, technically at least, straightforward and do not present major difficulties.

It is of interest to see how the various problems have been tackled by separate groups of investigators. Naturally, each of these has had a different approach because of different conditions and practical considerations which have had to be met. It should be remembered that it is only within the last year or two that a continuous culture of this kind has been shown to be practical; until then, experience of *Chlorella* and other related organisms was confined to the laboratories of a few interested botanists.

United States of America

Preliminary experiments provided a number of provisional answers to the problems which have been referred to. Thus it was found that the nutrient nitrogen usually supplied as nitrate (e.g. in fertilizers) could be more efficiently supplied as urea, though this is a much more expensive chemical; that increased carbon dioxide concentration had the anticipated beneficial effect; that the optimum temperature for the strain of *Chlorella* used was about 25°C, though a slightly lower night than day temperature produced better results; and that the ensuring of a uniform supply of micronutrients, and preventing their loss during handling, was greatly facilitated by the addition of a chelating agent, i.e. a chemical which can form complex compounds with these micronutrients, thus holding them in solution and releasing them only slowly.

The pilot plant which emerged from these investigations was ingeniously simple. It consisted essentially of a long sausage of the thin transparent plastic known as polyethylene, through which the culture was continuously circulated. When empty and flat the sausage was some 4 foot wide, and to begin with, two 70 foot lengths were joined by a U-shaped end-piece. Three such units, each modified as required by experience, were constructed one after the other during the latter half of 1951. There was, of course, a good deal of more complicated ancillary equipment, such as pumps for circulating the culture, a plant for the preparation and introduction of the necessary carbon dioxide/air mixture, centrifuges for harvesting the cells from suspension and, later, a heat exchanger for cooling the medium.

The operation of these units seems to have been sufficiently satisfactory to convince the American workers that the production of algae in a plant of this kind is technically possible. Naturally, a number of troubles were encountered. Thus it was found that if the culture was below a certain depth, the tube was unstable in a high wind; that the rate of flow had to be above a certain critical level to keep the cells in suspension; and that it was very difficult to keep the tubes from leaking, particularly where the sections were joined together. When leaks occurred, contamination with other organisms appeared to ensue fairly readily. It was also found that since free evaporation of water was prevented by the closed tube the suspension became very hot and a heat exchanger had to be put into the circuit; this is a fairly expensive addition to the plant required.

The first unit operated for some five weeks in all and naturally ran into most of the teething troubles; the second unit never functioned satisfactorily and the third operated for some two months at a not particularly favourable time of the year, October-December 1951. The average yield of the first unit over the whole period of its operation was about 6 grammes per square metre of illuminated surface per day; during a 42-day period when operating

troubles were at a minimum the average yield was approximately 9 grammes per square metre per day, and for a short period of 10 days 11 grammes per square metre per day were obtained. With the third unit, individual daily estimates of more than 10 grammes per square metre per day were obtained but the combination of contamination with other organisms and unfavourable weather led to an overall average of 2 grammes per square metre per day for the 52 days of its operation. Throughout, the algae showed about 50 per cent of its dry weight as protein.

It is worth noting that, assuming complete utilization of the visible spectrum (a large proviso, as has already been indicated), it should theoretically be possible to produce 110 grammes of dry algae per square metre per day. On the basis of the experience of this pilot plant, rough calculations were made to determine how far one might expect to get towards this goal. A reasonable average yield from the pilot plant was taken as 4 grammes per square metre per day. Since during much of the experimental period the average daily amount of sunlight was low (about 3 hours per day as compared with 12 to 14 hours during good weather in the summer), corrections for this factor indicated that under more favourable sunlight conditions some 20 grammes per square metre per day could have been realized with this equipment; this would have been equivalent to a rate of production of about 17½ U.S. tons per acre per year.

Germany

More or less simultaneously with the American work an interesting though contrasted approach was begun in Germany by Gummert. The original aim of this work was to investigate the possibility of utilizing carbon dioxide from waste industrial gases in the Ruhr. This was demonstrated to be possible provided the sulphur compounds were removed first.

During the actual experimental work only 1 per cent of carbon dioxide was used in the culture medium, in contrast with the 5 per cent by most other workers, and this no doubt partly accounts for the lower yields obtained. No attempt was made to keep the cultures free from contamination with other organisms, the algae being grown in tanks in a greenhouse and in plastic-lined trenches in the open air. The bubbling of the carbon dioxide/air mixture was relied on to maintain turbulence. The only temperature control provided was cooling for the greenhouse tanks during hot weather. The method of harvesting was again by centrifuge. It will be seen that the conditions were very much simpler than in the American work.

An indication of the results obtained will be found in Table II; the lower yield per litre in the greenhouse cultures can be attributed to the greater depth of culture used, the concentrations being lower in the deeper cultures.

The proportion of protein in the algae was of the order of 50 per cent of the dry weight and that of fat of the order of 2 per cent.

During this work contamination of the cultures with protozoa, particularly flagellates, became serious, and consequently many of the cultures became useless. Late in 1951 it was noticed that the alga *Scenedesmus* had a greater resistance to contamination than did *Chlorella*. Attention was accordingly turned to a strain of *Scenedesmus obliquus* and in the summers of 1952 and 1953 this alga was cultivated by Meffert under similar conditions in the open air and in greenhouses.[1] It is of great interest that no significant contamination was found with these cultures of *Scenedesmus obliquus*, while other cultures of *Chlorella* grown at the same time in 1952 and 1953 again showed contamination with protozoa. The difference in yields of algae was also most striking: *Scenedesmus* gave some two to four times the yield obtained with *Chlorella* (see Table II, p. 125).

Venezuela

The work which has been carried out in Venezuela is of a rather different kind to that pursued elsewhere. After some preliminary investigations of the plankton of Lake Maracaibo, mixed cultures of algae were grown in open bowls of unglazed clay. Evaporation from the porous sides kept the water to a reasonable temperature although the bowls were exposed to direct tropical sunlight. A thick 'soup' of algae was obtained from these bowls, and from 1942 to 1946 these plankton soups were used as accessory food for leprous patients at the Cabo Blanco Leprosarium; the patients apparently ate it readily, and it was possible to conclude that at least the algae did them no harm.

Israel

Israel has limited areas of arable land, a limited supply of water for irrigation, a rapidly expanding population and an acute shortage of protein. Any domestically-produced protein would save foreign currency and might therefore be attractive even if the price was slightly above the average world level. This combination of circumstances seems to provide particularly favourable conditions for the culture of algae.

After preliminary experiments on two or three different organisms, the same species of *Chlorella* (*Chlorella pyrenoidosa*) was chosen as in the American and German work, and laboratory experiments were begun in 1951 by Evenari and Mayer. They investigated particularly the possibilities of producing algae with the simplest possible plant (to save currency on imported materials) and with the greatest possible re-use of the culture

1. Unpublished work; private communication.

solution to save water. The algae were first grown in large glass flasks which were placed on a south balcony so that they received direct sunlight on about a third of their total surface. The airstream, which contained about 5 per cent of carbon dioxide, was again relied upon to produce agitation.

The authors of this work expect that, if a light utilization can be achieved that is three times as high as at present, either by continuous illumination or by exposing the entire culture instead of only one-third of its surface to the light, then a yield of 0.5 g/l/day can be attained even under these simple conditions. This presupposes a continuous harvesting system which will maintain the concentration of cells at the optimum level. The higher yields obtained here in comparison with those achieved under very simple conditions in Germany can presumably be explained partly by the better supply of carbon dioxide and partly by the much greater incidence of sunlight. Even so, the expectation of 0.5 g/l/day seems perhaps a little high when compared with the yields obtained in tubes and with artificial light in the United Kingdom (see below).

Both their own work and a study of the American work has convinced the Israeli that shallow depths of *Chlorella,* though they are more efficient in that they provide a greater density of organisms per unit volume of culture, are not practical in Israel, partly because of the intense heating effects to which they would be exposed and partly because of the uneconomic utilization of land areas which would result. They have also decided that no attempt would be made to keep the system sterile and that the introduction of carbon dioxide must have a maximum efficiency because of its high cost. These workers also intend to examine a diploid *Chlorella* (a genetical variant having double the number of chromosomes and obtained from Professor Pearsall's laboratory in London) which has very large cells, is said to have a division rate identical with that of normal *Chlorella,* and may therefore improve the yield per unit time.

United Kingdom

In the United Kingdom, M. J. Geoghegan has been working with *Chlorella vulgaris* which he has grown in the laboratory in cylinders, in a battery of large tubes, in large bottles, and outdoors in a tall plastic tank. Carbon dioxide was supplied mixed with air in the usual 5/95 per cent mixture, though later 20 per cent carbon dioxide in air was used, the same total amount of carbon dioxide being used in both cases. Intermittent blasts of air were found to be necessary to keep the culture in suspension, the frothing which resulted from this treatment being controlled by use of a silicone. Harvesting was again carried out by regular centrifugation.

It was found that the lag phase of growth could be eliminated and yields increased by inoculating with cells which were already in the exponential

growth stage. It was also found that the nutrient nitrogen could be more effectively supplied by compounds of ammonia rather than the usual nitrate. The tall tubes indoors gave the highest yield because they were illuminated with artificial light. The plastic tank outdoors was illuminated by sunlight only and the depth of culture was greater. The crude protein yield was again about 50 per cent of the dry weight.

Japan

An interesting unit has been operated in Tokyo by Professor Tamiya and his colleagues. Only preliminary results have been reported so far.

In this pilot plant the growth unit consists of a concrete trough covered with a transparent plastic sheet. The culture (this time of *Chlorella ellipsoidea*) flows through the trough, falls into a sump at the lower end, and from here is pumped to the top of a metal tower down which it then passes counter to a current of carbon dioxide, thus enriching itself in the gas before returning to the trough. Harvesting is by preliminary sedimentation in a vat, followed by final centrifuging.

This unit was run for 10 days in February 1953, the temperature at this time of the year being well below that found to be optimal for most strains of *Chlorella*. No particular trouble with contaminating organisms was encountered, but it was found that condensation on the inner surface of the plastic sheet cut down light transmission.

Theoretical calculations, which took into account the average temperature and the average light quantity per day in Tokyo, have suggested a possible annual yield of 10 tons per acre, a lower figure than that assumed by most other workers.

RESULTS

It will be seen from these brief accounts that, broadly speaking, the approaches have been of two kinds: the relatively elaborate, exemplified by the United States work, aiming first at getting the highest possible yields and leaving the economic cost of so doing to be determined later; and the relatively simple, based on a more cautious view of what is economically feasible, exemplified by the German work, which attempts first to see what can be done under the simplest and cheapest possible conditions. These differences reflect the fact that the supply of water, of carbon dioxide, the cost and availability of nutrient salts, the need for protein and, indeed, the whole economic and social background are bound to differ from one country to another.

These considerations make it clear that nothing is to be gained by attempting a comparison of the results achieved. In any case, much of the work

described is in its earliest stages, and whereas some workers express their results in terms of weight of algae per unit volume of culture, others prefer weight per unit area of illuminated surface, and direct interconversion of the results is not possible. Nevertheless it seems convenient to set side by side such quantitative data as are available so long as it is realized that no logical comparison between them is possible.

TABLE II. YIELDS OF ALGAE (*Chlorella* unless otherwise stated).

	Yield in grammes of dry matter		*Approximate protein yields*[1]
	per litre per day	*per sq.m per day*	*tons/acre/ annum*
Germany (1951)			
Greenhouse (best monthly average)	0.039	—	—
Open air (best monthly average)	0.055	—	—
Germany (1952) (Scenedesmus)			
Greenhouse	0.05-0.1	5-6[2]	3.5-4.5
Open air	0.1-0.2	8-10[6]	6-7
United Kingdom (1949-1952)			
Glass tubes (with artificial light)	0.44	15.3	11
Plastic tank	0.3	—	—
Israel (1951)			
Flasks in laboratory	0.1-0.2[4]	12	8.75
Projected tanks	0.5[5]	14.3[4]	10.5
U.S.A. (1951 pilot plant)			
Average 40 days	—	6	4.5
Average best 10 days	—	11	8
Expectation from this (correcting for climatic factors, etc.)	—	20	14.5
Japan (1953 pre-pilot plant)			
Average 10 days run	0.043	3.5	2.5

1. Assuming 50 per cent dry weight as protein. It should be remembered that the figures in this column are wide extrapolations; also that they are yields per area of illuminated surface, *not* per total area.
2. 1952. 3. 1953. 4. Average. 5. Hoped for. 6. Low estimate.

It is only realistic to compare these results with figures for normal agricultural crops (admittedly mainly maximum figures) as given in Table I. But they should also be compared with the theoretically possible yield of algae: a figure of 4 tons of dry material per acre in 8 days (about 180 tons per annum) has been mentioned in the literature as a potential achievement with *Chlorella*. Even if one takes the single laboratory scale experiment in which the highest efficiency was observed with *Chlorella* (some work in Holland referred to below) and extrapolates from that, the figure obtained is only 70 g/sq.m per annum or about 100 tons/acre/annum.

Algal culture thus has a long way to go if it is to realize its full potentialities. What then are the possibilities of success?

UTILIZATION OF ALGAE

Most of the work to date has been directed to the production of protein and seems to have resulted for the most part in material containing some 50 per cent dry weight as protein. Since the main purpose of this effort has been to produce food, it is odd that so little investigation has been recorded concerning the use of algae as food. This may of course be due to the difficulty of accumulating enough material for extended feeding trials.

Two such feeding trials have been reported, one in the U.S.A. and one in Great Britain, and in both cases rats seemed to do quite well on *Chlorella*, though no trial has yet been carried through to the second generation. The diet fed in the British trials contained 17 per cent of *Chlorella* and it was found that, as a source of protein, *Chlorella* was superior to dried brewer's yeast and to peanut meal but inferior to dried skimmed milk. Chemical analyses have shown that the protein of *Chlorella* contains all the 10 constituent amino acids which have been shown to be essential for normal healthy growth, but that, as in most vegetable protein, the content of one of these, methionine, is rather low. So far, no extended trials with *Chlorella* as such seem to have been carried out with human beings, though the experience of the Kon-Tiki and Alain Bombard expeditions, as well as the Venezuelan work recorded above, indicate that the mixed bag of general planktonic organisms is capable of sustaining human life. It should be noted, however, that the above feeding trials with rats were carried out with freeze-dried *Chlorella* in which it might be expected that the cell walls were thoroughly broken down. The digestibility of *Chlorella* has been suspected on account of its relatively thick cellulosic cell wall and Evenari and Mayer in Israel have recently been reported to have shown that ordinary oven-dried *Chlorella* is completely indigestible to rats.[1] This is a point of some practical importance since freeze drying would normally not be economic.

Apart from the question of whether one could eat *Chlorella,* there is of course the more practical question of whether anyone would want to. The present author can report that freeze-dried *Chlorella* has a strong but not unpleasant taste closely resembling spinach. An American tasting panel has reported, however, that the flavour was in some respects unpleasantly strong, and has also noted a lingering, mildly unpleasant after-taste, together with a noticeable tightening at the back of the throat, nauseatingly referred to as the 'gag-factor'. This would seem to do little to encourage the reluctant to make their own test. On this basis the chances of *Chlorella* providing on its own a major constituent of the diet would seem to be small, which is a pity because it appears on the whole to have good food value and a reasonably high vitamin content. However, in Japan, where sea-weeds are more

1. Unpublished information; private communication.

commonly eaten, Professor Tamiya has prepared a number of experimental recipes, including a mixture of powdered *Chlorella* with flour from which bread and noodles could be prepared. It is perhaps along these lines that the future for *Chlorella* lies. The possibility of using algae as an animal feeding stuff remains to be explored.

There are, of course, other possibilities for algae besides their use as foodstuff. They could, for example, be used as fuel. There appears to be virtually no prospect of this being an economical proposition in the foreseeable future. Their use as an industrial raw material is perhaps slightly more hopeful, mainly because of their minor and more complicated chemical constituents such as steroids, though these have not yet been very carefully examined. The most interesting example to date is a strain of *Scenedesmus obliquus* which has been found to contain about 0.2 per cent of chondrillasterol which is a possible starting point for the synthesis of cortisone. This content is thought to be too low to be of industrial interest and there has as yet been no report of significantly higher contents. Other strains of *Scenedesmus* have been shown to contain steroids other than chondrillasterol, but these possibilities have yet to be investigated.

The use of the major fat fraction has also received some attention, both as a food constituent and as a possible source of drying oils. The former possibility does not seem to have received much attention since the original German work, though Professor Pearsall's group at University College, London, is still actively interested in it. The latter seems to have encountered difficulties over low yields and extraction problems. In general, the main fat fraction is apparently a typical vegetable mixture. The protein fraction has been examined as a possible commercial source of amino acids and as a raw material for an artificial fibre; no success has as yet been reported, the obstacles being mainly economic. The same would appear to apply to the extraction of vitamins.

ECONOMIC OUTLOOK

It is obvious from this brief survey of possible uses that some hard economic facts are badly needed. Unfortunately, no cost data have as yet been published by any of the workers in this field, and no very firm conclusions can yet be drawn. Some generalities are obvious but seem to have been overlooked. Unless algal culture is to be regarded only as a means for the rapid alleviation of desperate protein shortages under conditions in which cost and palatability are not of decisive importance, the aim must be to produce algae at a cost competitive with that of ordinary vegetable protein such as peas and beans. The degree of palatability of algae, and their fat and vitamin contents—which are comparatively good—may give a little elasticity to the

price range. Algae can also be regarded as fat producers, and, of course, if they became the source of any industrial chemical of the value of a cortisone intermediate, their economic outlook would be revolutionized; but neither of these possibilities has as yet been sufficiently investigated.

The fact that algal culture, with a potential production per unit area much higher than that of conventional agriculture, would mean a saving of land, can hardly be a potent argument in its favour until the world shortage of cultivable land becomes very much more acute than it is at present. This saving of land, however, could be used to offset part of the high capital cost of algal culture. But it should be borne in mind that the very considerable technical effort and capital investment required for an algal culture project could, if invested in the improvement of normal agriculture, have an enormous effect on total yields merely by bringing less efficient farms up to the level of the average. Whether this would be the better thing to do, cannot of course be decided yet.

If one considers the case of areas in which there is a shortage of agricultural land, water, or protein, or all three, it is obvious that algal culture becomes a more attractive proposition, but even there it would be necessary to consider whether perhaps hydroponics, the development of fishponds, or food yeast might not be more suitable. In any case, the possible attractions of algal culture should not be used as an excuse for not thinking about the steady improvement of existing techniques and the abolition of economic and political barriers to the transfer of local agricultural surpluses to areas of need.

One conclusion at least seems possible: while it is obvious that the greatest yield of algae per acre must be sought and that this could be obtained from vertical tubes, there is general agreement that a plant based on the vertical tube idea would be economically out of the question. Apart from this one can at present only list the major cost factors involved: plant costs (capital and maintenance) on the one hand, and the cost of nutrient chemicals and carbon dioxide on the other. As for plant costs, no attempt has yet been reported even to compare the cement-trough with the polyethylene-sausage types of plant (the latter seem likely to have higher maintenance costs). Other major plant costs would be the provision of adequate agitation, of heat exchanger capacity (at least to the extent of cooling in hot weather) and of harvesting equipment. Only centrifuges have so far been used for this last purpose, but they seem uneconomical on a large scale. The last step is drying, and this is always an expensive process. All this adds up to a fairly formidable list of technical requirements and capital investment, and the plant would naturally need skilled technical manpower for its maintenance.

To turn to the cost of nutrients and chemicals, it has already been pointed out that the maximum efficiency of utilization of salts, carbon dioxide and water will only be achieved with continuous recycling of the medium after

harvesting. Fortunately, the early reports of the development of toxic effects have not so far been confirmed on the pilot scale. With continuous recycling chemical or fertilizer costs will of course be proportionately lower than for normal methods of cultivation *via* the soil, since waste would be avoided. The carbon dioxide required will be relatively expensive unless it is available as a waste product; the chelating agents and the silicones would be required only in very small quantities, but then they are very expensive chemicals.

Summarizing his experience, the British worker Geoghegan has said: 'It seems clear from our preliminary estimates that *Chlorella* would be too costly to produce solely for use as a food and that economical production is likely to depend upon the possibility of using one or more of its constituents as a basic material in chemical manufacture, any residue being disposed of to the best advantage'. He also considers that any use of artificial light is likely to be too costly. The American workers seem to have concluded that yields must approach about 20 g/sq.m/day before the production of algae can be considered an economic possibility.

The cumulative effect of all these considerations gives a somewhat depressing picture of the future of algal culture. It is certainly true that no one has yet succeeded in demonstrating that algae can be produced in quantity at an economic price. However, it should be borne in mind that any attempt to apply rigid economic criteria at an early stage as final standards of judgment would have stifled at birth many technological developments which have subsequently proved of the greatest importance; and algal culture is just at such a stage. What then is the outlook for the future?

EFFICIENCY OF LIGHT UTILIZATION

In many laboratory experiments on algae efficiencies of sunlight utilization varying from 30 per cent to 90 per cent have been reported as against 2 per cent for normal crop plants; and it was partly on this account that high hopes for algal culture have been based. However, in all the work done so far to produce algae on a larger scale the efficiency has been of the same order as that of the average crop plant. The reason for this seems to be that the process of photosynthesis consists of a long series of complex reactions of which light absorption is only the first; the rate-limiting reactions appear to be those later in the chain which can take place in the absence of light. Under normal conditions of direct sunlight this rate-limiting dark reaction prevents the plant from using more than a small fraction of the incident energy; the rest is wasted or converted into heat. It has now been demonstrated that under artificial light of much lower intensity than direct sunlight both algae and the higher plants can use at least as much as 20 per cent of this incident energy. Some of the most recent work in this field has been done by

Wassink and his collaborators in Holland with a strain of *Chlorella*, and they recorded a maximum efficiency of 23.5 per cent. It is this figure, derived from a single small-scale laboratory experiment, which, when extrapolated, gives the yield of 70 g/sq.m/annum or about 100/tons/acre/annum already quoted. The width of this extrapolation, and the discrepancy between it and the results achieved in practice on a larger scale are a measure of what remains to be achieved.

Starting from the assumption that there is far more energy in ordinary sunlight than can be efficiently used by algae or higher plants, it has been shown that equivalent yields can be obtained with a light which flashes on and off so that the plant material is illuminated for only a fraction of the total growth period. Following up this idea, it has been ingeniously suggested that if *Chlorella* were to be grown in a very much deeper layer than any which has been attempted so far, then, provided that the degree of turbulence were sufficient, this 'flashing-light' effect might be achieved by bringing the individual *Chlorella* cell to the surface momentarily, when it would receive high intensity illumination, and then allowing it to sink again to the darker depths of the culture. It was hoped that in this way much higher efficiency of light utilization could be achieved together with very much higher yields of *Chlorella* per unit area. It has not so far proved possible to put this idea to the test. It was found, in the American 'polyethylene sausage' apparatus in which speed of flow was relied upon, that flow rates of much under one foot per second were too low to prevent sedimentation. Rates of between 1 and 1.5 feet per second were effective in preventing sedimentation but, at these speeds, no convincing demonstration was obtained of the 'flashing light' effect. It was further shown by theoretical considerations that under these conditions any attempt to increase the turbulence by increasing the flow rates might well produce highly undesirable hydromechanical effects such as destructive waves. If use is to be made of this flashing-light effect, on which much of the hopes for obtaining really high yields seem to rest, a quite different kind of apparatus may have to be envisaged.

OTHER ORGANISMS

As has already been indicated, there are five major groups of algae, and it has always seemed somewhat surprising that so much attention has been devoted exclusively to *Chlorella*. The reason for this is no doubt that *Chlorella* was a relatively well-known organism and that it existed in various botanical laboratories where it had been used as an experimental material. However, it is by now fairly clear that *Chlorella* in fact suffers from some disadvantages. To begin with, it has a relatively thick cellulosic cell wall, which not only reduces the proportion of useful material but may render the

cells indigestible, as has indeed been indicated by the experiments of Evenari and Mayer in Israel. Moreover, it does not appear as hardy or resistant to contamination—at least under some conditions—as was formerly imagined. In this connexion, the recent work of Gummert's group in Germany, in which *Scenedesmus* was found to be much more resistant to infection than *Chlorella* and to give yields up to four times as great under the same conditions, is of the greatest interest. In fact, when we consider the many thousands of other organisms included in the five groups of algae, we realize how lacking in detailed knowledge we are. The possibilities of genetical variants of known strains have yet to be tested. A diploid strain of *Chlorella* has already been mentioned. Even more interesting is the isolation by Myers in Texas of a strain of *Chlorella* which grows at an optimum temperature of 39°C, compared with the normal 25°C. Other things being equal, the use of such a strain should considerably cut down the heat-exchanger capacity required.

The full potentialities of algal culture can hardly be assessed until our knowledge of such topics is more complete. In particular, the blue-green algae offer interesting possibilities.

These are a relatively primitive and little known group but have in recent years been examined more closely by Fogg in the United Kingdom. Their main interest lies in their ability to fix atmospheric nitrogen so that chemically combined nitrogen—usually nitrate or urea—would not have to be supplied and the costs would be correspondingly reduced. One might envisage a mixed culture of blue-green and ordinary algae in which the former would fix sufficient nitrogen for both.[1]

Again, sea-water organisms have a considerable attraction since, if sea water could be used, the supply of nutrients required might be somewhat less; moreover, there would be less chance of bacterial contamination. Raymont at Southampton and the low temperature research station at Cambridge are now beginning some work on marine planktonic organisms of this kind.

CONCLUSION

In some ways the most interesting result of the work to date has been the demonstration of the depth of our ignorance of a large and varied group of organisms which has been known to botany for many years. The basic case for algal culture remains the theoretical possibility of obtaining an extremely high yield of protein per unit area on ground which need not be fertile. The best published results to date show that practical achievement still falls far short of this theoretical goal and there is as yet no suggestion that algal

1. W. H. Pearsall, 'The Utilization of Algae and Industrial Photosynthesis', *The Times Science Review*, Spring 1954.

protein can be produced at a price anything like competitive with protein obtained by more conventional methods. If algal culture has any future at all, it will no doubt first be seen in those territories where the incidence of direct sunlight is high, where there is an acute shortage of protein or of currency to buy protein, and where carbon dioxide is available as a waste material, though not all of these conditions need to be present simultaneously. However, much more research work remains to be done before we can get a clearer picture of the possibilities. If the results so far obtained do not justify the hope that the culture of algae will provide a quick and easy solution to the world's food problem, it should be remembered that many a technological development which held out even less promise has subsequently proved of the greatest value.

BOOKS AND PUBLICATIONS

Machines and Men

TUSTIN, ARNOLD, *The Mechanism of Economic Systems.* An Approach to the Problem of Economic Stabilization from the Point of View of Control-System Engineering, Heinemann, London, 1953, xi + 161 pp., 25s.

The simple act of picking up a fork, for all its ubiquity, is not easily understood, nor could it be explained by most of those who do it every day. It is, however, a clear example of a pervasive phenomenon known as feed-back control. Wherever we have purposive action we need some reliable and efficient method of achieving the end in view. The straightforward way of doing it is to use the amount by which the action has not yet attained its goal as a criterion for altering the action so as further to reduce the discrepancy between desired result and achieved result, and to go on doing this until we have removed the discrepancy or until the situation has changed. The full recognition and understanding of this general kind of behaviour must be reckoned as one of the outstanding positive achievements of research during the last war. Its significance has been, to some extent, obscured by the more spectacular and more threatening discoveries of atomic science.

Characteristic of our time is the rapidity with which this concept has been elaborated and the range of problems to which it has been applied. In the thirties there were only a few isolated examples, but by now it has effected something like a revolution in engineering as well as in military tactics. But one of its most interesting qualities is the extraordinary virtuosity with which it has found uses in other fields. In the guise of computing machines it is having an important influence on mathematics. Most unexpectedly it turns up in the field of language, with the startling proposition that information constitutes a kind of order and, hence, we are led to relating communication with entropy and one of the oldest branches of natural science. Beyond this the speculations quite naturally have carried a few of the bolder spirits straight into some of the central problems of philosophy, in particular those of free will *v.* determinism and of mechanism *v.* vitalism. Thus, while the elements of these control systems are simple and Newtonian, they are ordered in such subtle and complex ways that their behaviour does not conform to our simpler notions of a 'machine'. They have memory; they learn by experience, and they change their character and behaviour as a result of their own 'personal' life history.

What is happening is that we are getting much closer to robots, not the obvious kind that were much in people's minds several decades ago, but more workmanlike and serious ones. No one can be blamed for not having foreseen that it would be a matter of valves, RC circuits and the like. The feed-back amplifier seemed chiefly destined to bring an added pleasure through radio and little more. But in fact the ingenious application and further understanding of feed-back have led to design of control devices of such variety and excellence, that the comparison with human control was

bound to come; it came sooner and was carried further than might have been expected, mainly as the result of the audacious imagination and brilliance of Professor Norbert Wiener's book, *Cybernetics*.

Just as the body regulates its temperature and its chemical constitution by subconscious feed-back control, so also does it use feed-back in its more conscious acts, such as picking up a piece of chalk, driving an automobile, or aiming a gun. The fact that a servo-mechanism can aim a gun better than a man should make us pause and think about the implications of these machines. In his active and useful life man is mostly either making decisions (controlling) or supplying simple mechanical power. Any control which can be formulated by a definite series of instructions can be simulated by a control system; what is not so easy is the duplication of many human actions. But then it has always been held that the distinctive quality of man was his thought, not his power output; for power supply there are other and ever-improving machines, as well as beasts of burden. Apart from the practical implications of this fact, it is certain that a great step forward has been made possible in our understanding of both the mind and the body. The results have already been impressive in neurology and physiology; now we may expect them in the social sciences. Professor Tustin's book is the first to attack this problem and for that reason alone is an important work. Control mechanisms are constructed from parts with known characteristics, and these complicated machines can be observed under simple and controlled conditions, so that in this way we arrive at an understanding which is unattainable in the study of man in his natural setting.

Thus consumers regulate purchases by their bank balances and by their stocks of goods as well as by their income. Similarly business men make their decisions on the basis of bank balances, liquid assets, stocks of finished goods awaiting sale, stocks of raw materials, rate of output now and in the near future, price and market behaviour and no doubt many other such things. These all represent 'human-link' feed-back loops, because, say, a stock of finished goods leads to alterations in the rate of production, which will in turn affect the stock of finished goods. Surprising as it may seem, this general type of analysis has been little investigated in economics, and the fact that Professor Tustin shows the way is a step forward. But the matter does not end here. We have these 'subsidiary feed-back loops' all embedded in some very complicated larger feed-back system. Thus businesses have some level of sales; this leads, in one way or another, to a rate of production and disbursement of salaries, wages, and other payments; these latter, however, become in turn (are fed back to) the sales of the businesses. Hence we may heartily agree with Professor Tustin that 'the systems of interdependent quantities or "dynamic models" that are discussed by economists, are similar, not only in general type, but often also in the details of their relationships, to the systems of interdependent quantities that engineers consider when designing automatic controls'. The immediate consequence of this is that some of the rich armoury of analytical tools developed by control system engineers becomes available to the economist, and, no doubt, to some of the other social scientists. In fact the main purpose of the book is to explain the nature and use of these tools to the economist.

Striking confirmation of the hypothesis that economic and control networks are similar is to be found in the fact that both easily develop instabilities due to the fact that their own behaviour is fed back to them

altering further their behaviour, and also in the fact that this instability tends to show itself in perpetual oscillations ('hunting' for the right action but always overshooting) of a more or less harmful nature. Professor Tustin's incursion into economics comes at a favourable moment in its development, for in recent years a number of quantitatively formulated and relatively precise theories of the cyclical behaviour of the economy has been put forward. Indeed it must have been the existence of this type of theory, which the engineer finds understandable and congenial, that persuaded a distinguished scientist like Professor Tustin to give serious thought to the problems of analysis faced by economists. The methods so neatly and patiently explained in the book should reach a small but influential group of economists who will be receptive to them and ready and willing to make further use of them. Economists will find that the author has taken the trouble to make himself familiar with a considerable body of the recent literature, and they will not find anything gauche about the way their concepts are handled.

The first, and indeed the basic, thing that Professor Tustin sets out to show is that the concepts and methods of control-system engineering are applicable to economics. In itself this is not terribly obvious, but he shows without difficulty the very close analogy between these two apparently unrelated subjects. In servo-mechanisms we have a number of quantities which are related in a complicated way, and it is the art of analysing such intricate systems which constitutes the new discipline. Once we think of it, there is no doubt that an economy is much the same general sort of thing. Thus sales control production, and production leads to incomes but these, in turn, upon being spent become sales and so on. This is a typical 'feed-back loop' or closed causal, dynamical sequence and its similarity with control systems is impressive. Consequently when Professor Tustin makes a diagram of the interdependence scheme of an economic model[1] it looks very much like the kind of diagram to be found in books on servo-mechanisms. For this reason he does not have to invent new theories; he has only to translate modern econometric theories into his own language.

An ingenious and satisfying activity no doubt but, the sceptical economist will ask, is it really useful? Of course it is, and we can only hope enough economists will read far enough in this book to see why. The reason is to be found in the vastly superior analytical tools at the disposal of control system engineers. Through the elaboration of the operational calculus, they have developed incomparable methods and profound insights into complicated systems. The engineers have all the advantages; they know the component parts of their machines; they can re-arrange or alter them almost at will; and they can observe and record their behaviour under all sorts of controlled input and load conditions. Undoubtedly the absorption of even a small part of this know-how in economics will be of great service. Such transfer of these techniques is already familiar to scientists and has been enormously fruitful, as in acoustics which has benefited by the importation of analogies and methods from electronics.

As his first task Professor Tustin has to explain to the scientific layman the methods employed in the analysis of systems, and this he performs (in

1. For an example of this, see *Impact*, vol. IV, No. 2, Summer 1953, p. 91-100.

Chapter III) with great skill and patience. If he is less than completely successful, the fault lies with the inherent difficulty of the problem. The operational calculus can be treated in a very forbidding way, and at its lowest level requires considerable knowledge of, and more particularly familiarity with, mathematics. Professor Tustin's presentation is probably the least difficult exposition of this analysis yet published. He achieves his result by consistently using graphical methods with great skill and to good purpose. This has, however, more than a pedagogical justification, for the data, both in engineering and in economics, are commonly given in the form of empirical curves, and it is upon this basis that we must derive our conclusions. In most cases this means we will be confined to graphical analysis in any case.

In the final reckoning the test of a thing is its usefulness. Can this sort of engineering analysis be actually used to give us the answer to any of the economic troubles that plague us? The crucial issue is undoubtedly the question of whether or not it can help us to get rid of the devastating instability of our delicately constituted economic mechanism. This issue which is perhaps the best point on which to test the book is also the one which is the most interesting and vital to us all. We do not come away empty-handed.

Unwanted and harmful oscillations are an old story to the engineer. Engines vibrate, wheels shimmy, ships roll, radios and gramophones boom or screech, and so one could continue to enumerate a very long list of excessive and unwanted vibrations. A great part of all machines have to be altered in some way or another to lessen or eliminate this mal-functioning, and out of all this experience has come a great deal of knowledge about general methods of attack on such problems. It is one of those really new, seminal ideas to apply some of this engineering experience to the task of eliminating perhaps the gravest social problem of our time. Professor Tustin does not claim to have the answer already neatly arranged for use, but what he does propose is a joint assault on the problem by economists and engineers.

'Perhaps economists will consider this a pipe-dream of a technologist accustomed to systems more concrete and manageable than the worlds of business, finance and politics, but there seems to be a case for an examination of these possibilities by some group of qualified economists and engineers under the patronage for example of the Board of Trade or the Department of Scientific and Industrial Research, or both jointly.'

There are two ways to get rid of parasitic oscillations. The obvious and old-fashioned way is to redesign the mechanism, but this is not easy with a private enterprise economy and, happily, it is not the best way. The brilliant new approach is to add to the mechanism a new set of causal dependences (a feed-back loop) which will continuously correct itself so that its performance is always of a high order no matter under what varied conditions it may be working. It is interesting that the advice of the engineer in this respect has been intuitively anticipated by the economists. In the old days economists were always trying to solve the malaise of booms and slumps by tinkering with the economy, i.e. by altering the behaviour of the banking system, sometimes by weakening monopolies and cartels, at others by stimulating them, by helping the farmer, by fostering or discouraging research, by breaking trade unions or by promoting them, and finally, and

most drastically, by socialism or the shift from private to public control of the economy. There was no agreement on what changes were needed, but all agreed that some changes were necessary. Since the publication of Keynes' *General Theory of Employment, Interest and Money,* there has been an almost universal shift of opinion away from controlling the economy by altering its structure. The preferred policy now is to control it by skilfully varied government fiscal policy. But this is precisely a 'supplementary feed-back loop' of the kind beloved by communications engineers. The behaviour of the economy is to be watched by economic experts who report to the government any tendency to boom or to slump. On the basis of this the (ideal!) government takes prompt and sufficiently strong action (through a budget deficit or surplus) to lower or to raise the total national spending by just enough to keep it on an even keel. Thus the behaviour of the economy is filtered (studied and used as a basis for policy) back to itself as a basis for its own control. Anyone who has listened to a modern high-fidelity sound reproducer (with heavy negative feed-back) will know what extraordinarily splendid results can be achieved with this method. Do we really have within our grasp a similar (and very much more important) advance in social control?

The answer, of course, is no, but at the same time we have some grounds for hope. What has never been specified, even abstractly, by economists, is the timing and size of these governmental counter-cyclical interventions. This is not a matter of detail, for if the intervention is too little or too late, or if it is too much and too soon, it is well known to the engineers that this can give rise to the phenomenon known as 'hunting', whereby the situation is made worse instead of better. Wherever there are complicated inter-dependences with compounded dynamical effects, it is indeed a delicate matter to design a good automatic control mechanism, but this is, alas, what we desperately need.

Into this muddled situation Professor Tustin brings new light. Taking an admittedly over-simplified model of the economy, he actually synthesizes, *quantitatively,* the necessary feed-back loop to give an unstable economy the desired degree of stability. In doing this he does what has never been clearly even conceived before: he specifies the timing and magnitude of government action to increase or decrease national income. If his results do not give us an actual recipe, they do show the sort of thing that needs to be done and point out the directions in which our efforts must be made. It is one thing to calculate what is needed and quite another thing to 'realize' it physically (as all natural, but not all social, scientists know). The formula that Professor Tustin arrives at for fiscal policy makes the size of government activity look a bit forbidding, but in saying why he thinks the situation is not so bad, he demonstrates a proposition which many economists have felt but none has ever tried to prove. The point is that if government intervention could be properly timed and of the right size, then there would not be serious variations of output and income, and hence the government intervention would not have to be large. This sounds devious (and it is this which has made the more circumspect economists wary of it) but it really is not, as is proved many times every day by the great accuracy of many electronic control mechanisms.

'The general inference from a study of stabilizing devices is however that when they are functioning, and are in fact correctly designed to ensure

stability, the "work" they do is surprisingly slight. It is a matter of *slight* additional stimulus to the system, precisely timed so as to offset and suppress any initial tendency for an oscillation to build up, so that it never does build up. It nips the oscillation in the bud.'

Unfortunately Professor Tustin leaves the problem just before indicating which of two basic types of stabilization is relevant to economics. For example, there is radar tracking of aircraft, in which the stability means that the output (direction of finder) is kept close to the input (the direction in which the plane lies). This agile behaviour is exactly what we do *not* want in an economy. Rather we want a mechanism stable in the double sense, first, that it gets where it is going quickly and, second, that it is always tending to a constant or slowly changing value. An example is the mechanism whereby bodily temperature is maintained within a narrow tolerance under the most varied conditions. Or again take the case of driving. If we like to keep a steady pace of 40 m.p.h. regardless of the slope we are on, then we act as a human link closing the feed-back of speed used as a controller of power input. Now if we follow current trends, we shall eventually merely set a dial for the speed we want and the servo-mechanism will do the continual trial and error adjustments for us and, indeed, possibly better than we could do it. Yet to state the problem is to see the nature of the difficulty—the type of power control that would work best would be different for different kinds of hill or, generally, for different terrains. Therefore we must specify the load in terms of the probability of encountering slopes of each steepness, and then find some 'best' compromise behaviour. Much superior work was done on this problem during the late war, notably by Professors Norbert Wiener and Ralph Phillips. There is, I think, no doubt that this is the nature of the economic cycle problem, and it is therefore the greater pity that Professor Tustin did not exercise his skill at graphical exposition to explain these difficult matters in simple terms. The result would have been, no doubt, to kill off even more of his potential lay readers. But a bold assault might have carried the day, since economists, whatever their general mathematical inadequacies, are reasonably familiar with statistical concepts. The average economist is less shy of conjectural variables than is the average engineer.

After giving, in the first three chapters, a thoroughgoing demonstration of the meaning and use of the analytical tools in terms of a few current but highly schematized models, Professor Tustin goes on to discuss the much more difficult problem of how to get closer to the complex reality of an economy. He gives a penetrating analysis of the dynamical nature of the circular flow of purchasing power in terms of sales, stocks, rates of disbursement and of delivery. While the recognition and formulation of these problems are not new, an altogether higher level of analytical power is displayed, an achievement which should have a lasting influence on economic theory. From this he proceeds to the more controversial subject of the determinants of investment. Here, along with consideration of some current theories, he also presents some novel suggestions of his own on how to formulate the problem.

Beyond the difficulties of constructing some usable, but sufficiently complicated, realistic theory, we come to a still more fundamental difficulty: there are probably serious non-linearities in the economic structure. The moment

this is admitted the validity of a great part (but happily not all) of the analysis is destroyed. In losing linearity we lost a great deal; it has sometimes been said that the dazzling achievements of modern electronics are a direct consequence of the wide range over which linearity assumptions are valid.

But engineers grapple with non-linearities and often (but not always) come off victorious. Professor Tustin is undaunted by the problem and produces what is perhaps his most striking proposal—to construct large-scale mechanisms strictly analogous to the economy. We may build into the machine all the non-linearities we wish, since we do not seek general solutions but only particular answers to particular problems. The analogue computor play-acts our problems for us and tells us with authority what would be the consequences of various policies. With this information we may take more intelligent action in dealing with the delicately articulated motion within the economy. If this programme does not succeed the fault will lie with the economists, not with the engineers. No amount of analogues can tell us what are the laws of behaviour of the parts of the economy; they can only tell us, given such and such a structure, how the interplay of events will shape the evolution of the system. In spite of some appearances to the contrary, the economist is not adequately prepared to supply technical data on the characteristics of the component parts of his machine. Yet we need not entirely despair. We can probably try a more limited and partial analysis of special problems with some chance of success. And then the mere statement in clear terms of what we need to know helps to re-direct effort towards more fruitful collection of data. Thus one of the most useful points in this book is the tactful insistence that the kind of time series analysis done by many econometrists is unlikely to be entirely successful. This is no fault of the economist. Any scientist knows that, given a very complicated machine, the parts of which are unknown to us, we are very unlikely to be able to calculate its structure from observations on its behaviour—especially if these are under uncontrollable conditions.

In his Chapter VI, Professor Tustin gives a brilliant survey of the arsenal of analogue components available and likely to be useful in dealing with economic problems. This is his métier and he speaks with authority in as nearly non-technical language as possible. This part of the book—and indeed the whole of it—will become invaluable if he has the success which he deserves and hopes to have in convincing some private or public body to undertake further investigation of these fascinating possibilities.

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